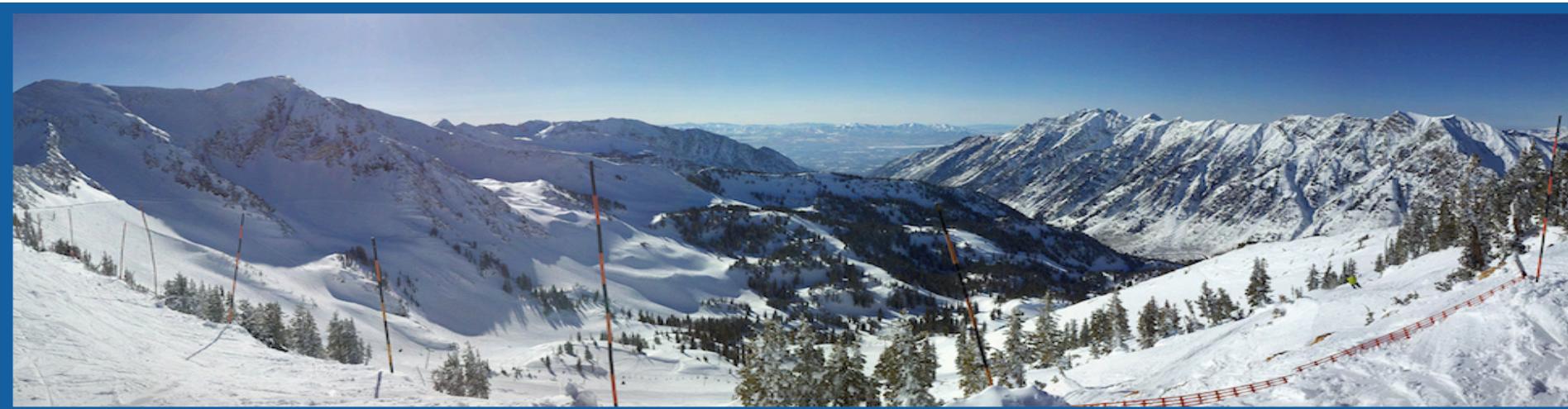


# Studies of B to J/ $\psi$ decay with the Forward Silicon Vertex Detector (FVTX) at PHENIX Experiment

Xuan Li (LANL)

For the PHENIX Collaboration



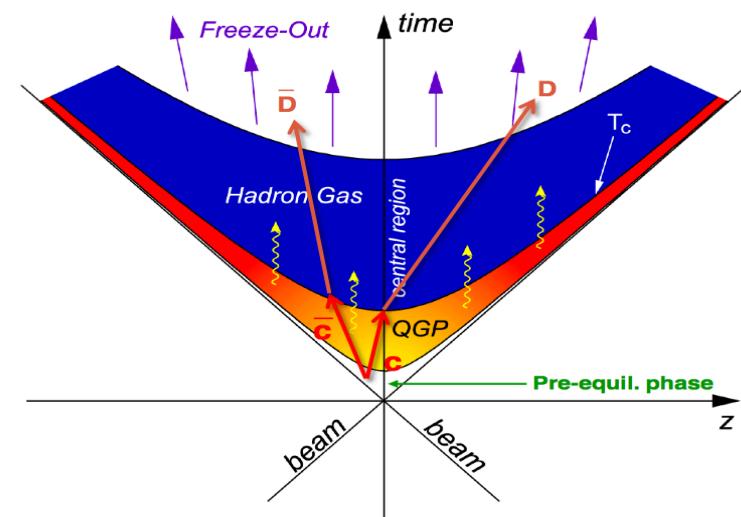
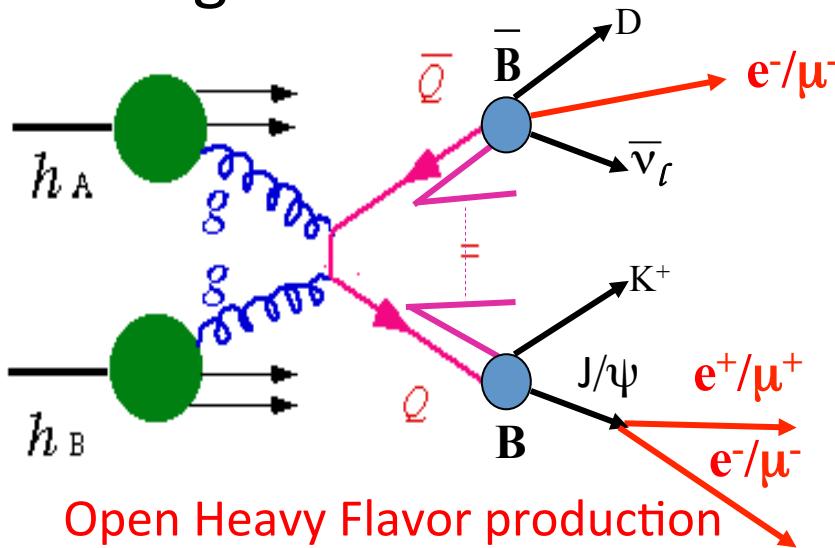
The 33rd Winter Workshop on Nuclear Dynamics

# Outline

- Motivation.
- PHENIX and the Forward Silicon Vertex Detector (FVTX).
- PHENIX Forward B to J/ $\psi$  measurements
  - in 510 ([arXiv:1701.01342](#)) and 200 GeV p+p collisions to study the energy dependent B hadron production.
  - in 200 GeV Cu+Au collisions to explore heavy flavor production interaction with the medium ([Cold Nuclear Matter](#)/ [Hot Nuclear Matter](#)) .
- Summary and Outlook

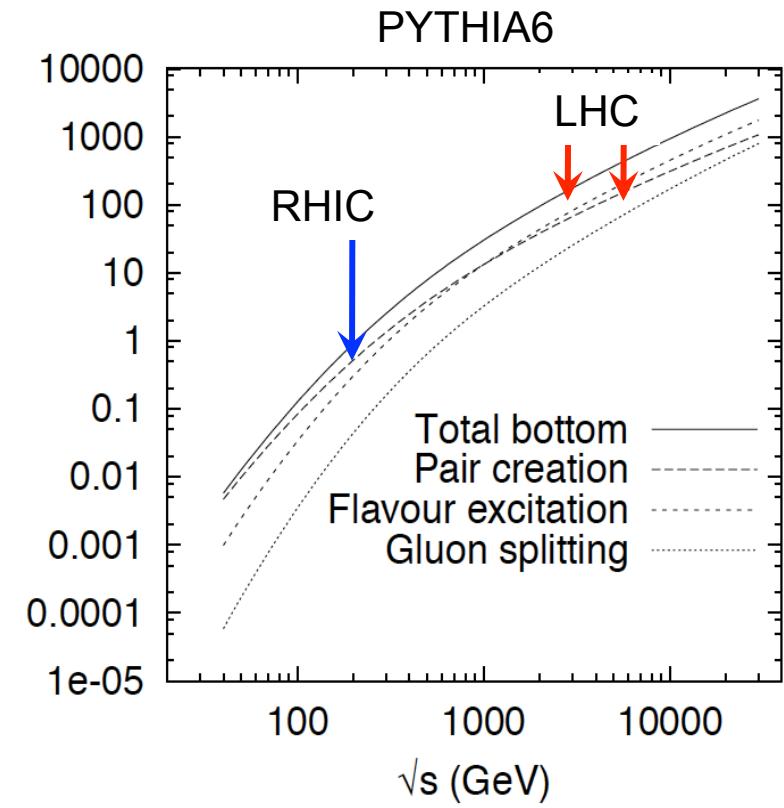
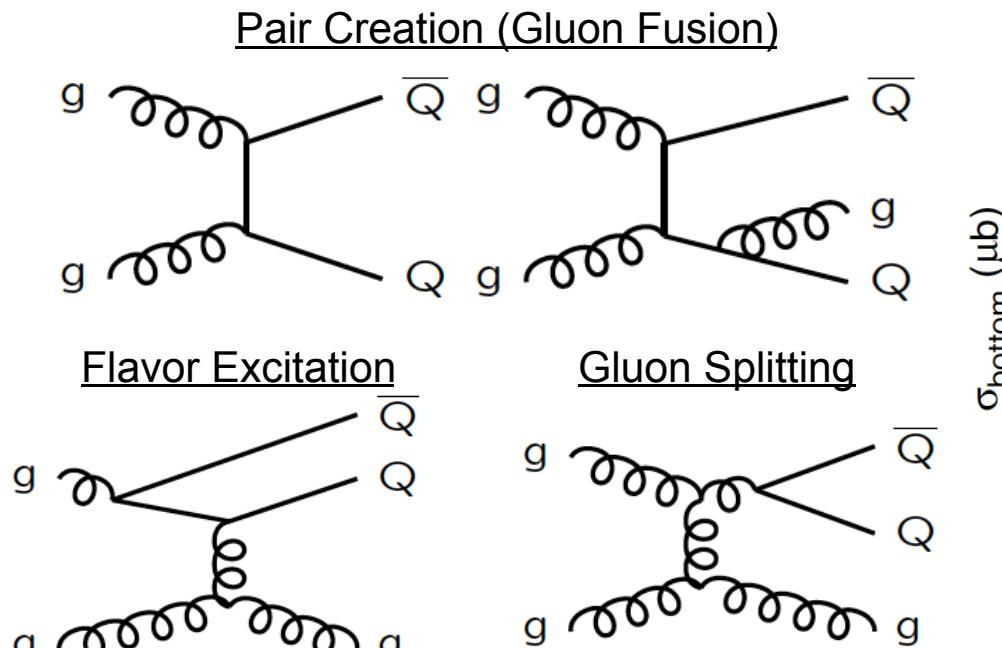
# Motivation

- Heavy flavor production is a good probe to study the full evolution of the medium as it is produced in the early stage of nuclear collisions due to its high mass ( $m_{c,b} \gg \Lambda_{QCD}$ ).
- The heavy quark can traverse the whole evolution of the system as interactions with the medium do not change the flavor.



# Uniqueness at RHIC

- Uniqueness at RHIC
  - dominated by pair creation (gluon fusion), clean interpretation for experimental results.

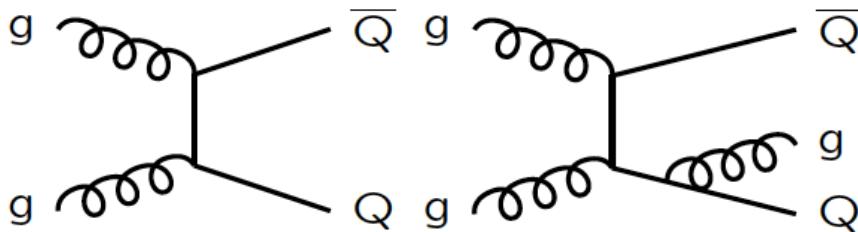


T. Sjostrand, EPJC17 (2000) 137

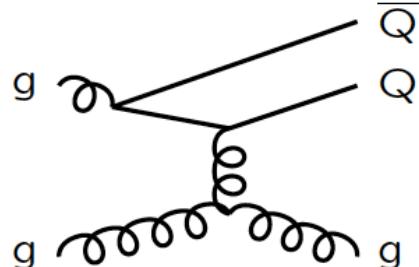
# Uniqueness at RHIC

- Uniqueness at RHIC
  - dominated by pair creation (gluon fusion), clean interpretation for experimental results.
  - accesses complementary kinematics region compared to **LHC** measurements.

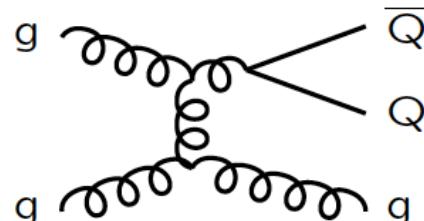
Pair Creation (Gluon Fusion)



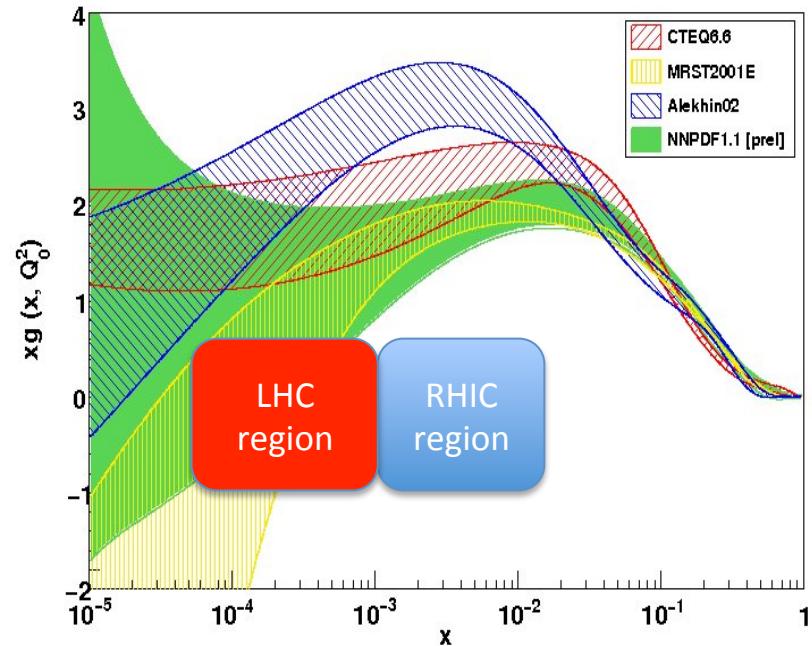
Flavor Excitation



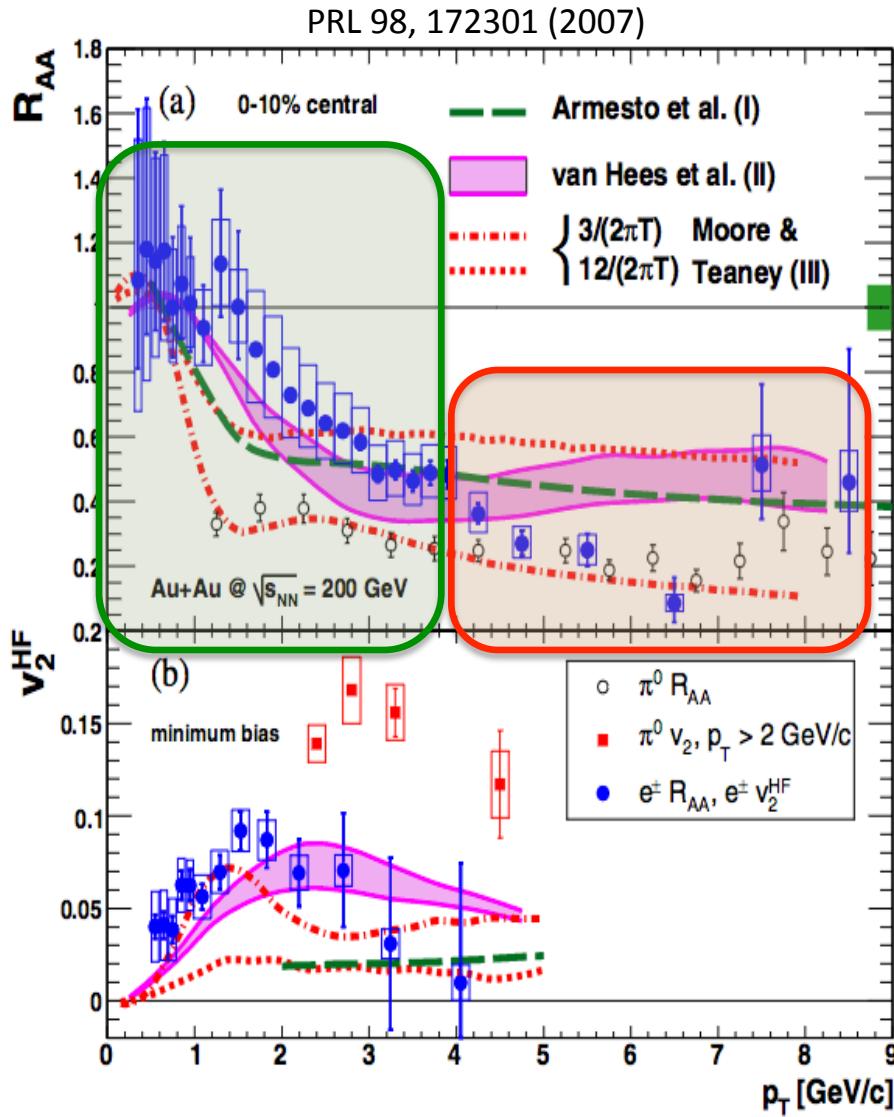
Gluon Splitting



Nucleon Gluon PDF



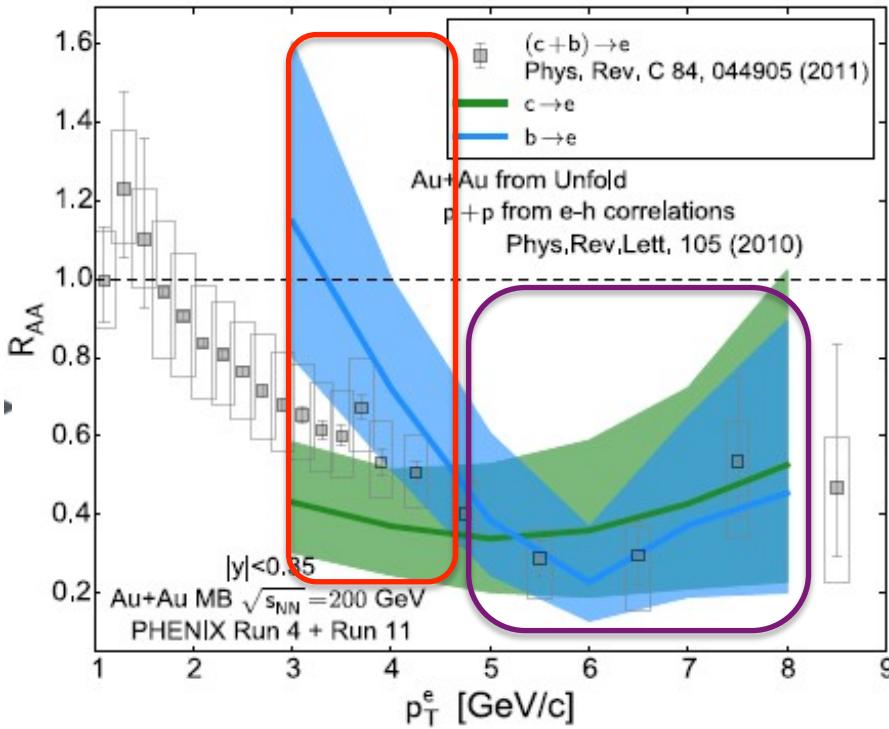
# Surprise in Au+Au heavy flavor measurements (QGP formed)



- Suppression of the inclusive Heavy flavor  $R_{AA}$  and non-zero  $v_2$  provide evidence of strong coupling between the heavy flavor and medium.
- Similar suppression of  $R_{AA}$  between the inclusive heavy flavor decayed electrons and light hadrons in high  $p_T$  region.
- Different suppression of  $R_{AA}$  in the low  $p_T$  region.
- Mass/Flavor dependent  $E_{loss}$ ?

# Indication of flavor dependent energy loss

PRC 93, 034904 (2016)

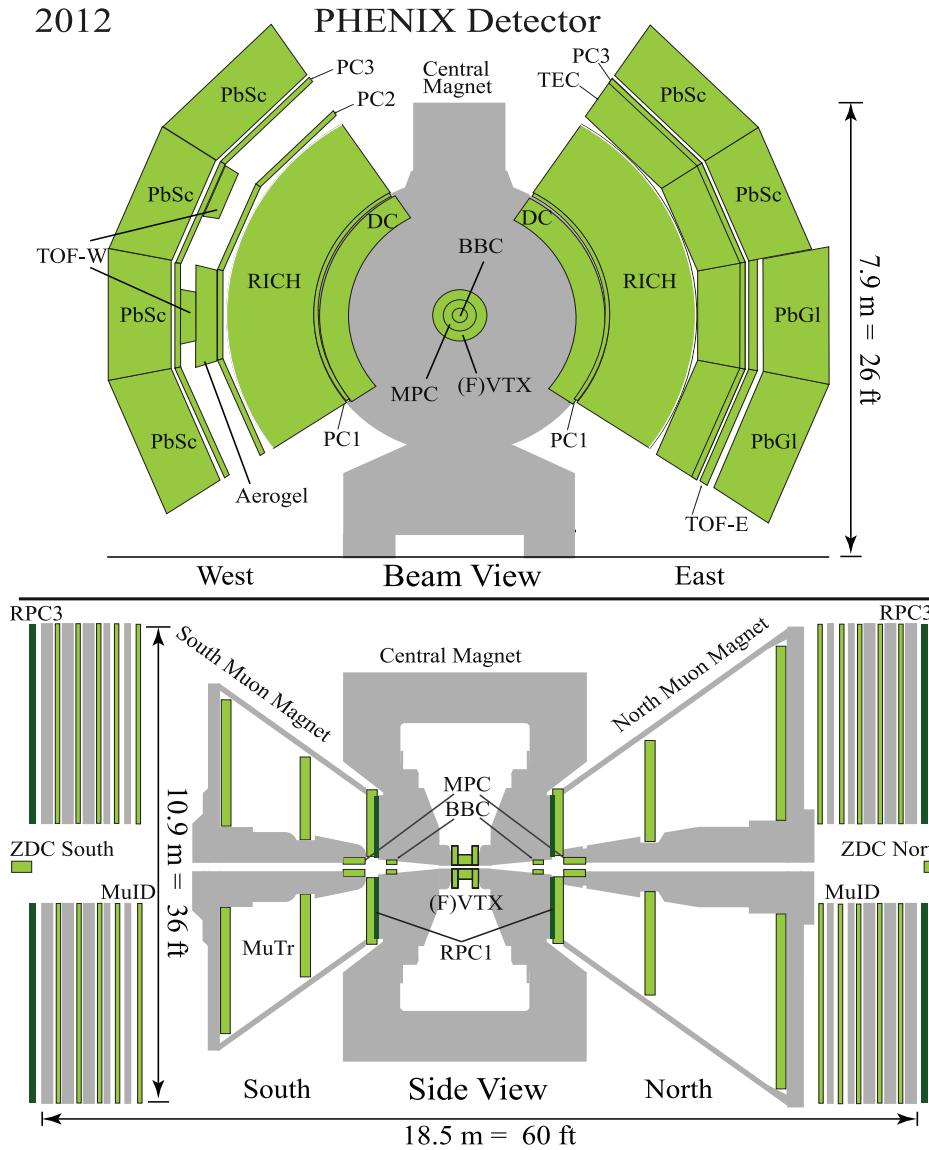


- From the PHENIX **charm** and **bottom** separated single electron R<sub>AA</sub> results,
  - Bottom has similar suppression as charm for high p<sub>T</sub> region.
  - Bottom may be less suppressed in the low p<sub>T</sub> region.
- Consistent with Energy Loss mechanism:
$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

- Is **bottom** production less suppressed than the **charm** production at forward rapidity in the **low p<sub>T</sub> region**?
- Measure B hadron directly at RHIC?
- Need to first understand the B hadron production
  - in p+p collisions.

# PHENIX detector

2012



- **Central Arm (Electrons)**

- $|\eta| < 0.35$
- $\Delta\varphi = \pi$
- Tracking: DC, PC, VTX
- eID: RICH, EMcal

- **Forward Arms (Muons)**

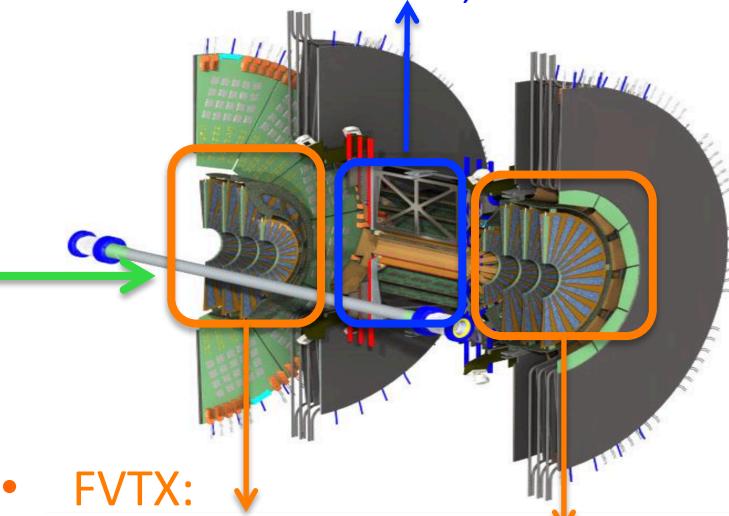
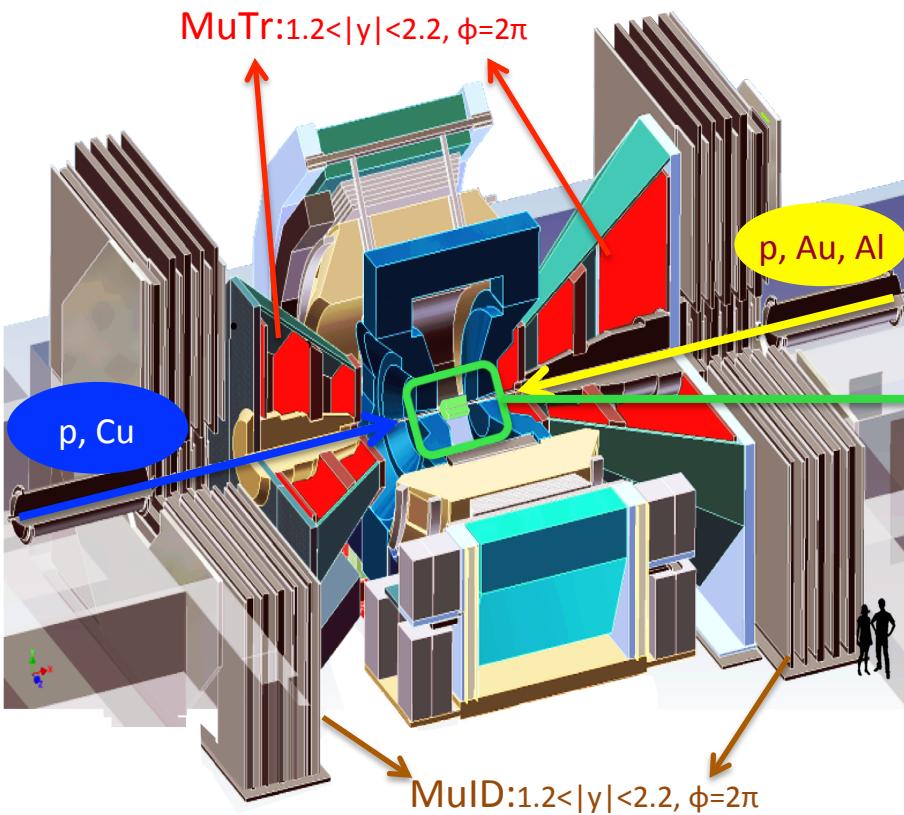
- $1.2 < |\eta| < 2.2$
- $\Delta\varphi = 2\pi$
- $\sim 10$  interaction length absorber
- Tracking: wire chamber, FVTX
- MuID: muon identification detector

# Silicon Vertex Detectors of PHENIX

- The silicon vertex detectors: **VTX**(installed since 2011) and **FVTX**(installed since 2012) make the new heavy flavor measurement possible in p+p, p+Al, p+Au, Cu+Au and Au+Au collisions.

- VTX:**

- With  $|y| < 1.2$  and  $\phi \approx 2\pi$  coverage.
- provide precise vertex and tracking measurements for  $D, B \rightarrow X + e$ .



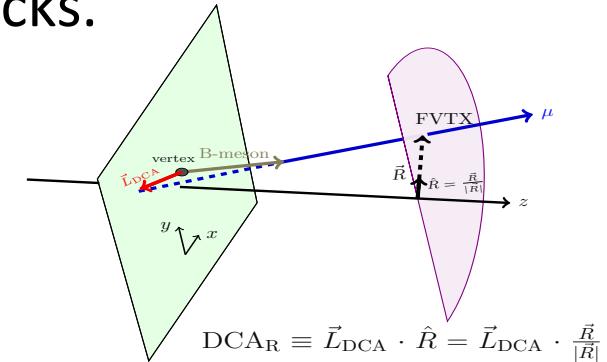
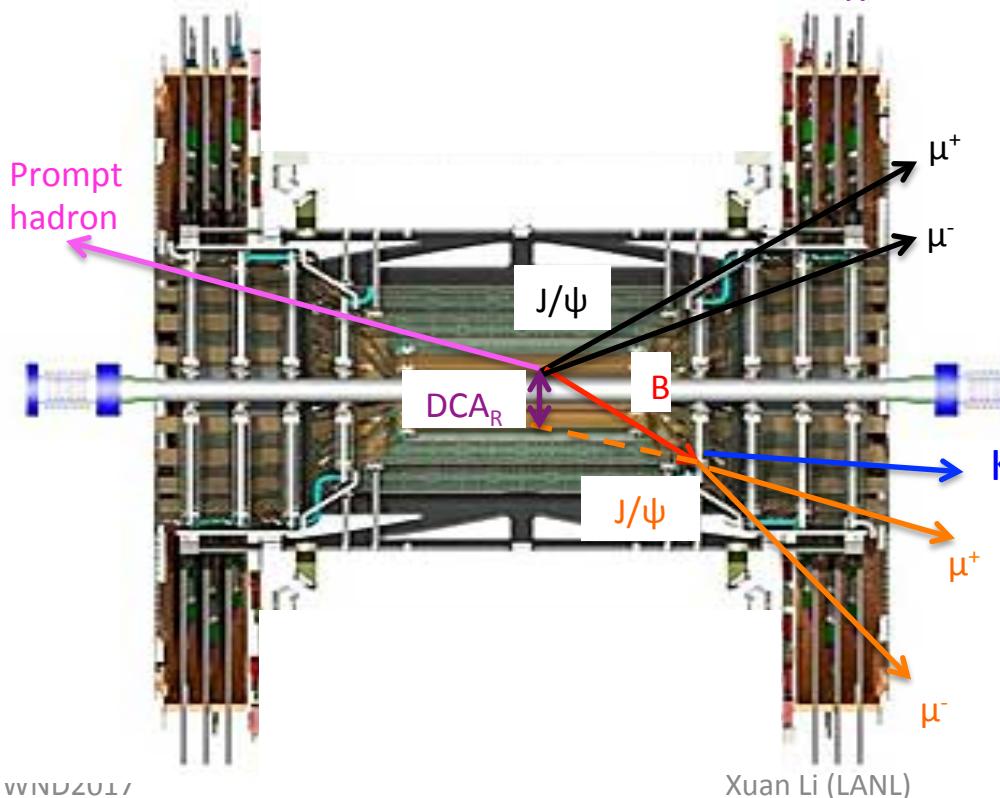
- FVTX:**

- With  $1.2 < |y| < 2.2$  and  $\phi = 2\pi$  coverage.
- provide precise tracking and DCA measurements for  $B \rightarrow J/\psi$  and  $D, B$  separation.

# Can we measure B meson in forward rapidity?

$$B \rightarrow J/\psi \rightarrow \mu^+ \mu^-$$

- **B hadron** decay length ( $c\tau$ ), about the size of hair diameter:
  - $c\tau(B^0)=455\mu\text{m}$ ,  $c\tau(B^\pm)=491\mu\text{m}$ .
- **B hadron** is further boosted at forward rapidity.
- FVTX can precisely determine the Distance of Closest Approach along the radial projection ( $\text{DCA}_R$ ) of tracks.



- Different shapes of  $\text{DCA}_R$  of prompt particles and decayed particles make the separation of **B** decayed **J/ $\psi$**  and prompt **J/ $\psi$**  feasible.

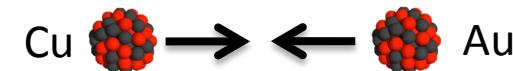
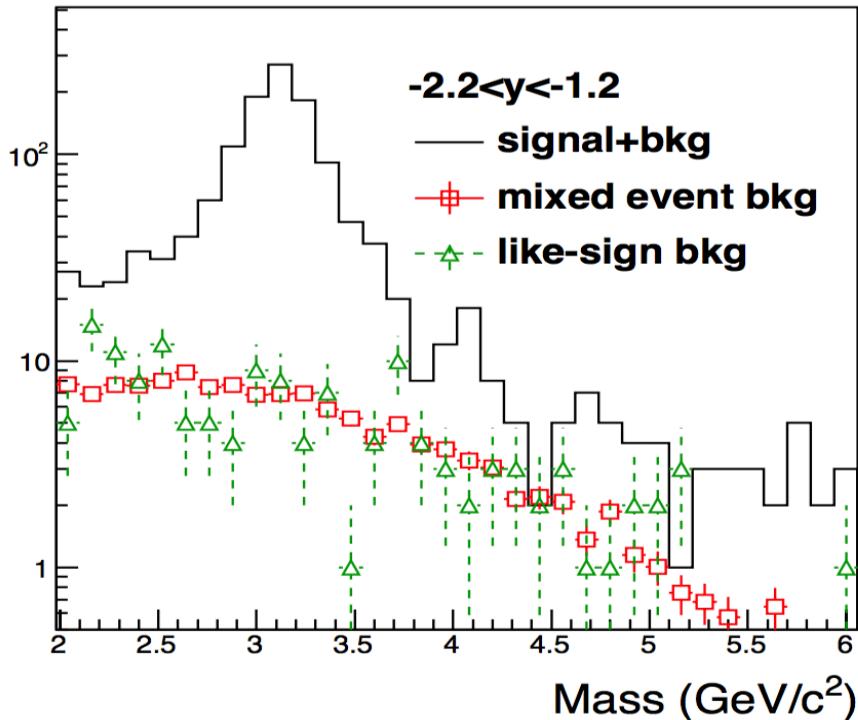
# How to determine the J/ $\psi$ from B-meson decay?

- In p+p and heavy ion (eg. Cu+Au) data:
  - Identify the J/ $\psi$  candidates from di-muon mass spectrum after applying quality cuts.
  - Use the FVTX to determine the DCA<sub>R</sub> of muons from di-muon pairs in data.
  - Use simulation (embedding) with realistic detector condition and collision environment to determine the muon DCA<sub>R</sub> shape from prompt J/ $\psi$  and J/ $\psi$  from B-meson decay in p+p (Cu+Au) collisions.
  - Determine various background components.
  - Simultaneously extract the prompt J/ $\psi$  and B-meson decay J/ $\psi$  through fitting on data.
  - Apply the acceptance\*efficiency corrections.
  - Calculate the systematic errors.

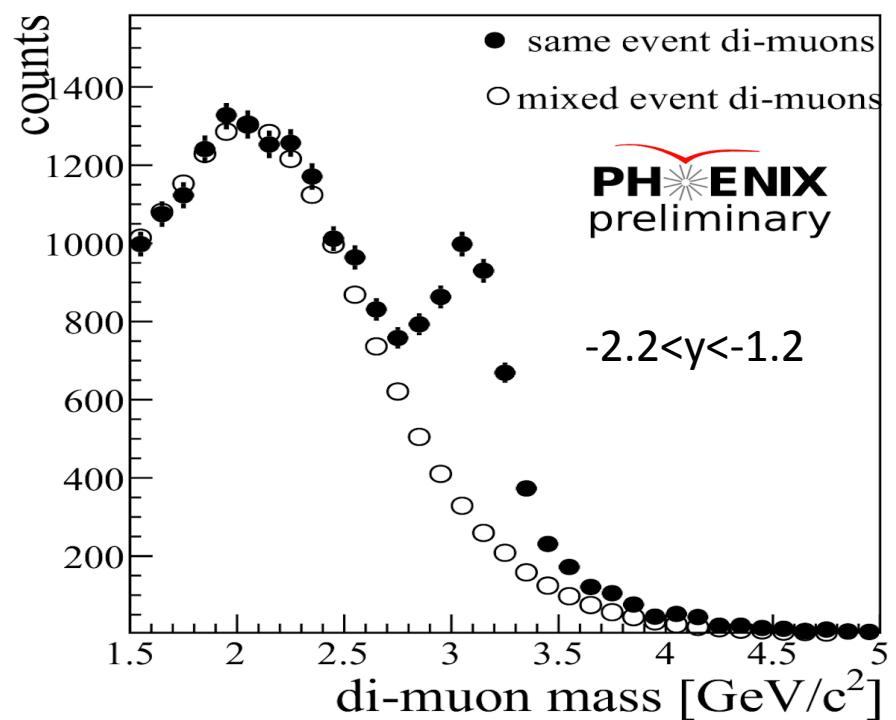
# Analysis strategy for the B to J/ $\psi$ ratio measurement (I)



2012 510 GeV p+p data



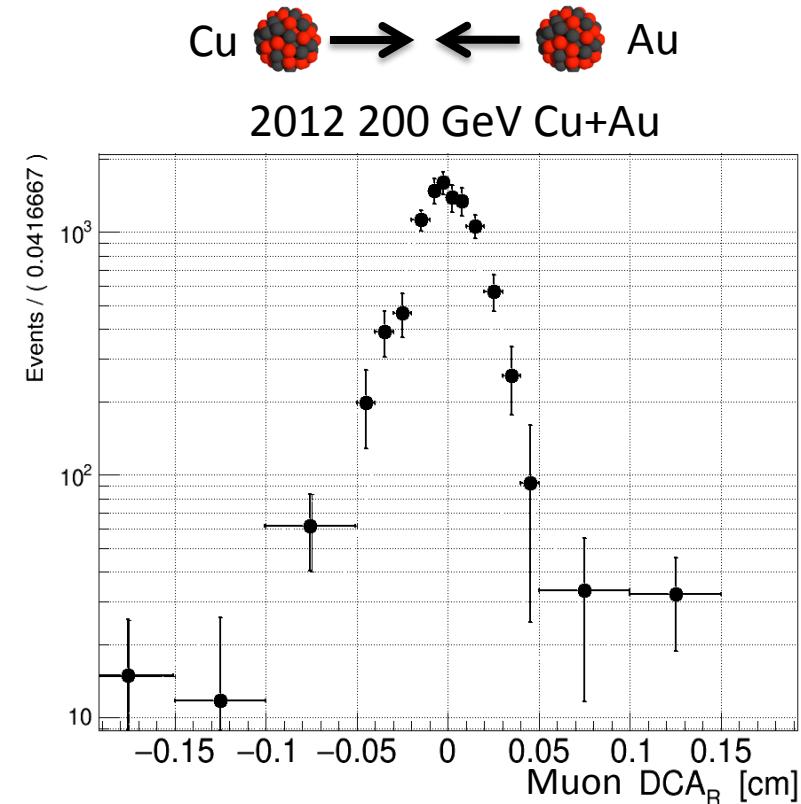
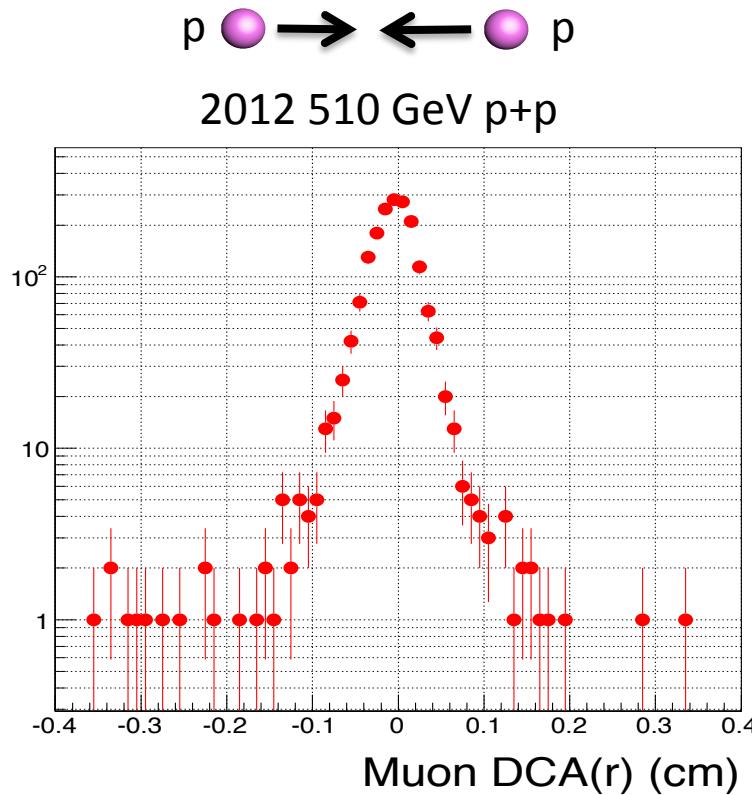
2012 200 GeV Cu+Au data



- Clear J/ $\psi$  peaks are found in both p+p and Cu+Au data.

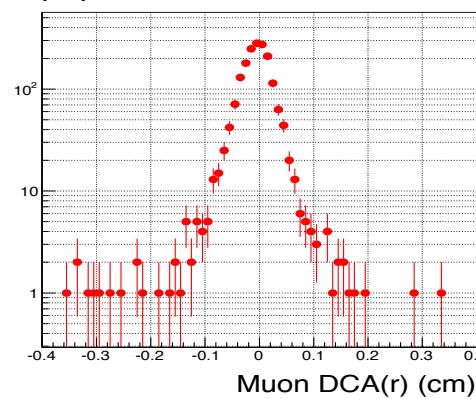
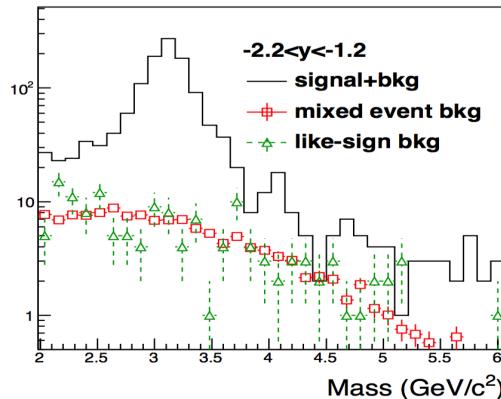
# Analysis strategy for the B to J/ $\psi$ ratio measurement (II)

- After select good J/ $\psi$ s, require the muon track of di-muon pairs matching to the FVTX and measure the DCA<sub>R</sub>.
- Muon DCA<sub>R</sub> measurement in data with -2.2 < y < -1.2:



# Analysis strategy for the B to J/ $\psi$ ratio measurement (III)

2012 510 GeV p+p data

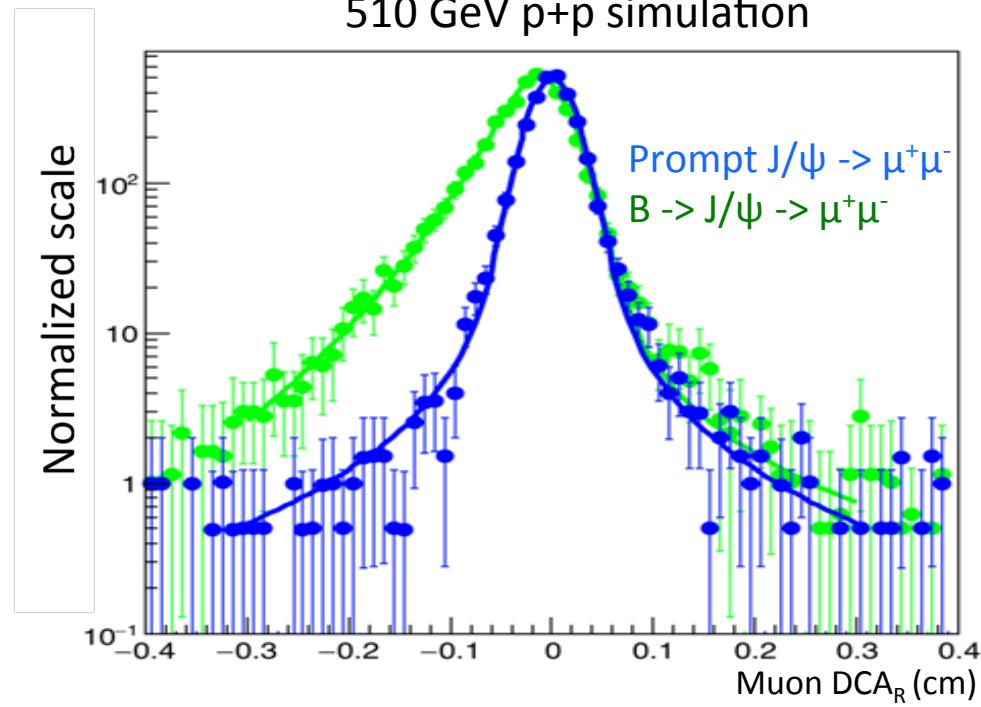


- Clear J/ $\psi$  peaks are found in both p+p and Cu+Au data.
- Muon DCA<sub>R</sub> determined in data.

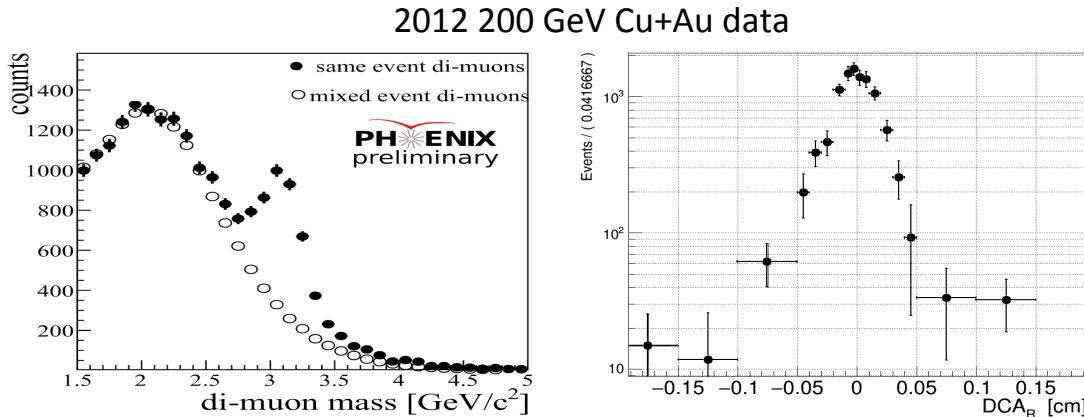
## • Signal determination

- Generate prompt J/ $\psi$  and B to J/ $\psi$  events in full simulation (PYTHIA +GEANT+RECO) for p+p with realistic vertex and dead maps etc.
- Obvious DCA<sub>R</sub> shape difference between prompt J/ $\psi$  and B to J/ $\psi$ .

510 GeV p+p simulation

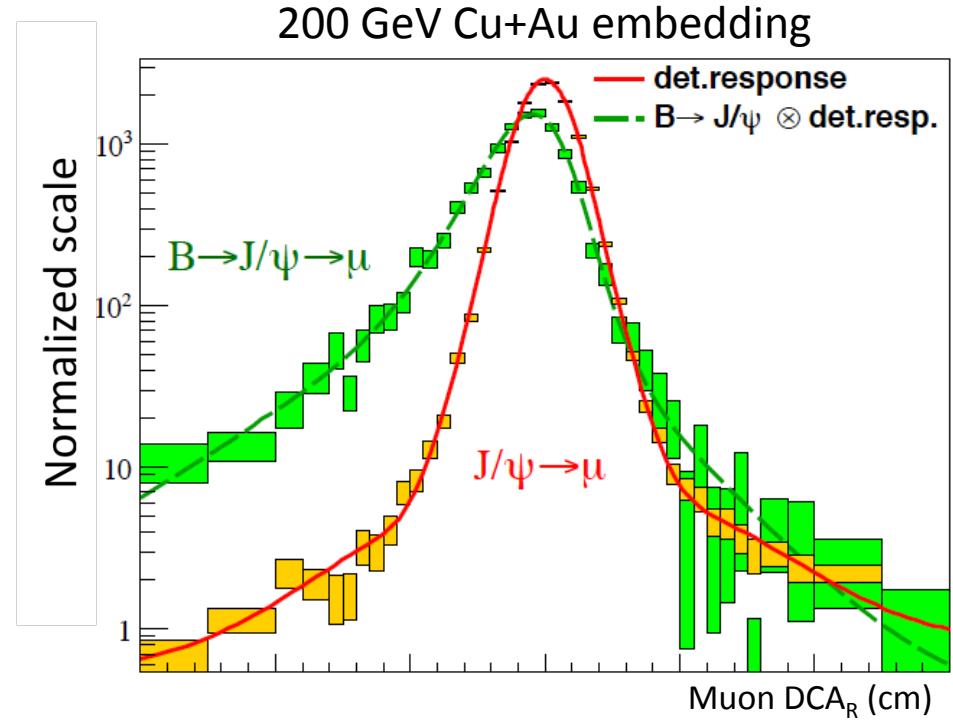


# Analysis strategy for the B to J/ $\psi$ ratio measurement (III)



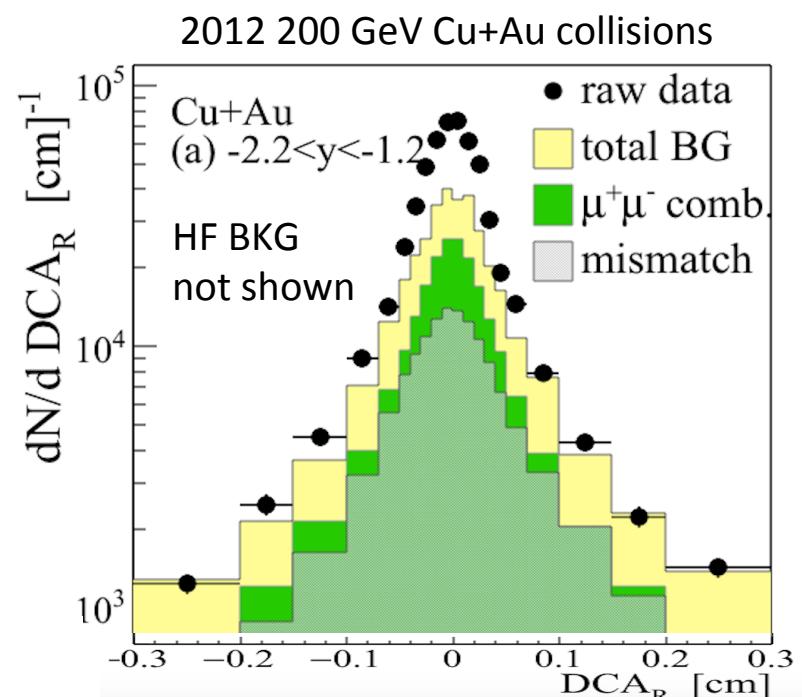
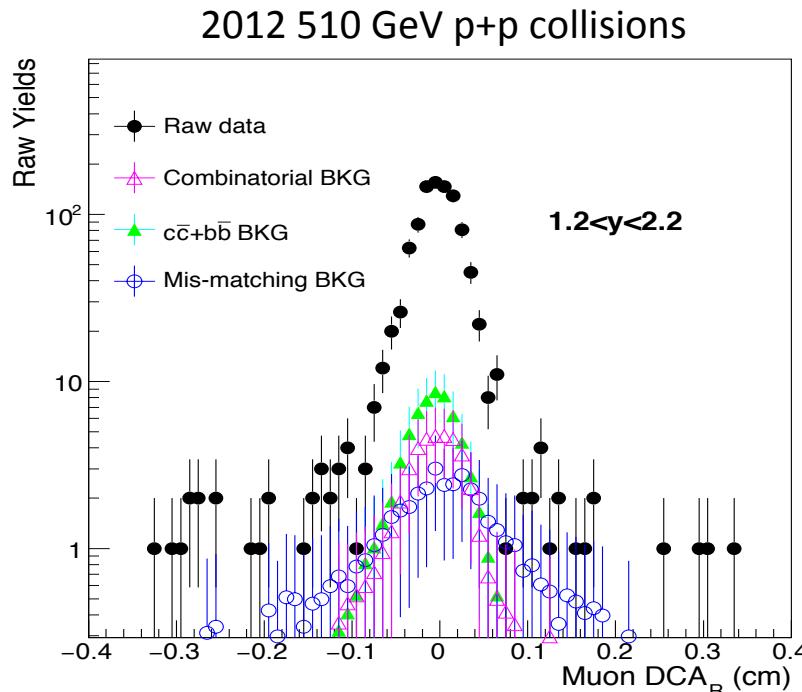
- Clear J/ $\psi$  peaks are found in both p+p and Cu+Au data.
- Muon DCA<sub>R</sub> determined in data.

- Signal determination**
  - Generate **prompt J/ $\psi$**  and **B to J/ $\psi$**  events in embedding for Cu+Au with realistic vertex and dead maps etc.
- Obvious DCA<sub>R</sub> shape difference between **prompt J/ $\psi$**  and **B to J/ $\psi$** .



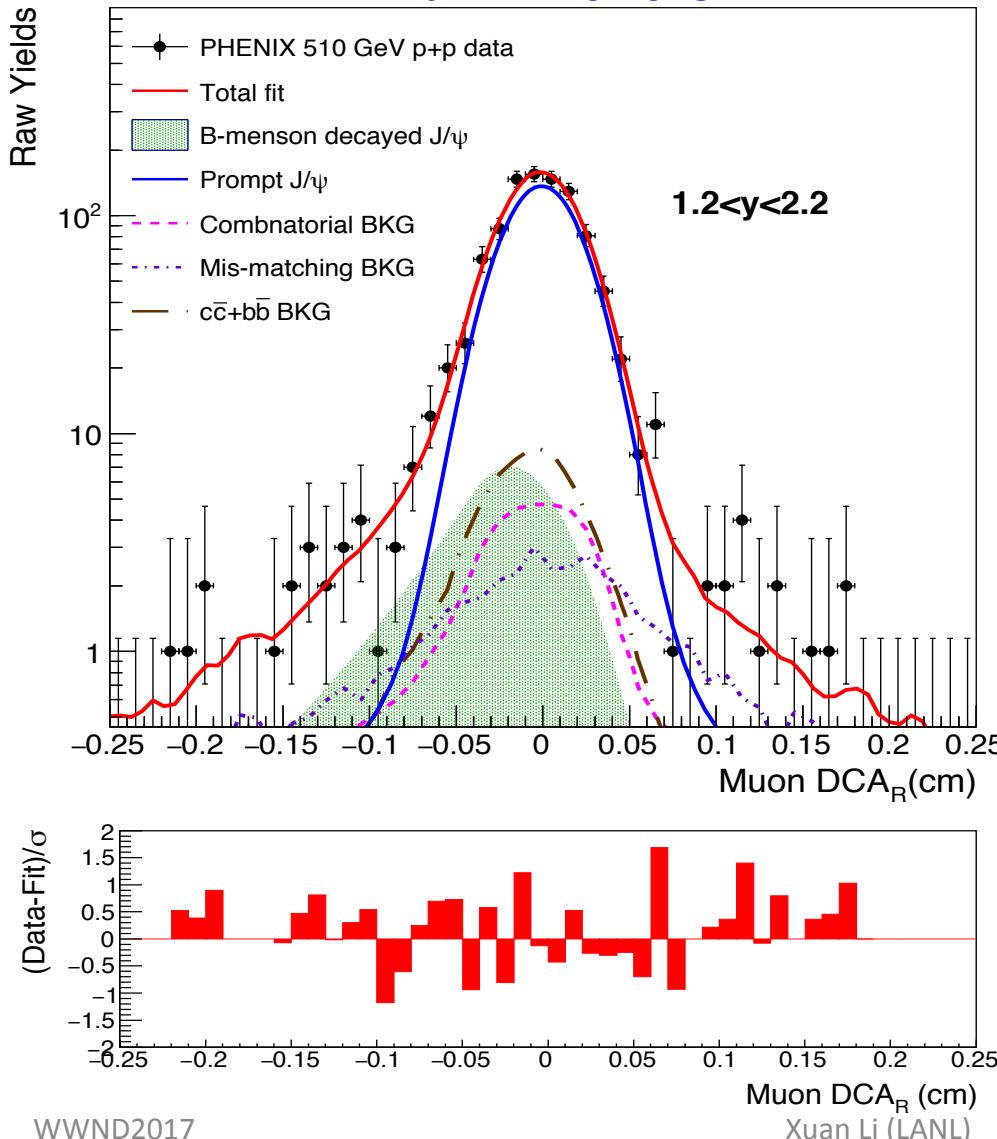
# Analysis strategy for the B to J/ $\psi$ ratio measurement (IV)

- Background determination
  - Dimuon combinatorial background using mixed events.
  - FVTX-Mutr track mis-matching using topological detector event mixing technique.
  - Heavy flavor continuum (dominated by ccbar), generated in simulation with fraction determined in data.



# Analysis strategy for the B to J/ $\psi$ ratio measurement (V)

PHENIX arXiv:1701.01342

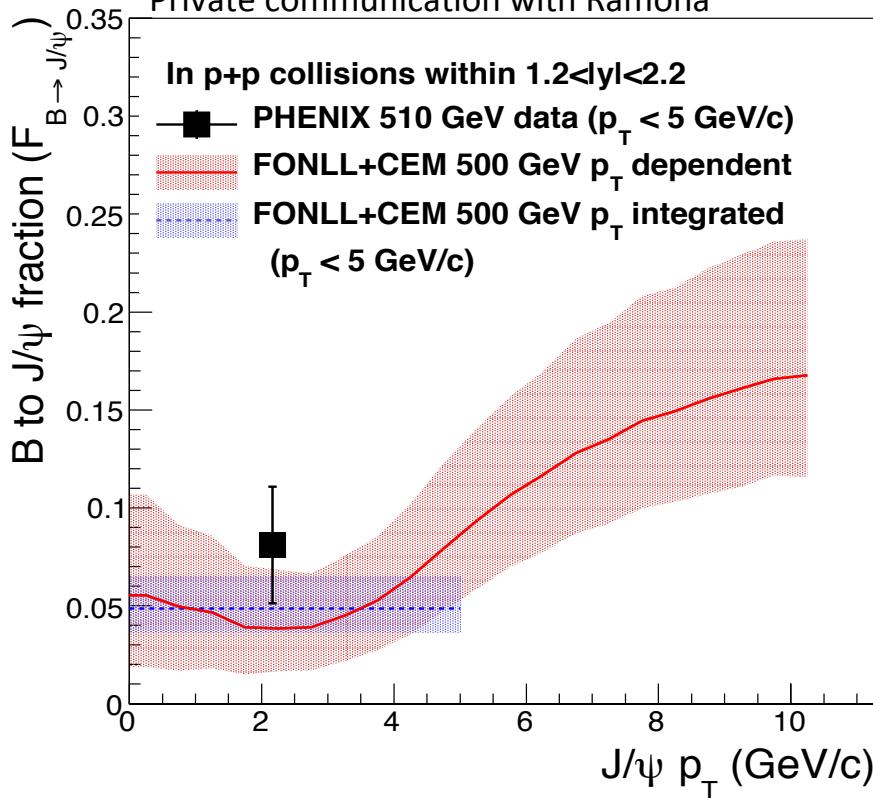


- Fit on DCA<sub>R</sub> in data to simultaneously determine the **prompt J/ $\psi$**  and **J/ $\psi$  from B-meson decay** yields and extract the B to J/ $\psi$  fraction.
- Apply the relative acceptance\*efficiency correction to B to J/ $\psi$  fraction result.

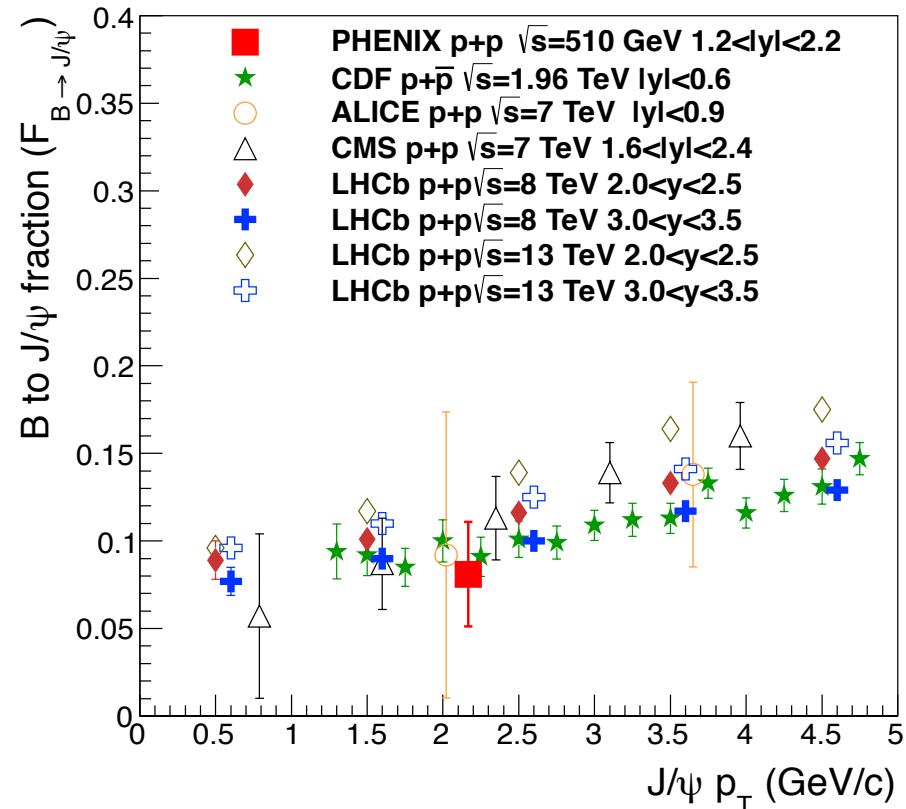
# B->J/ $\psi$ fraction in 510 GeV p+p data

FONLL+CEM: Phys. Rev. C 87, 014908 (2012)

Private communication with Ramona

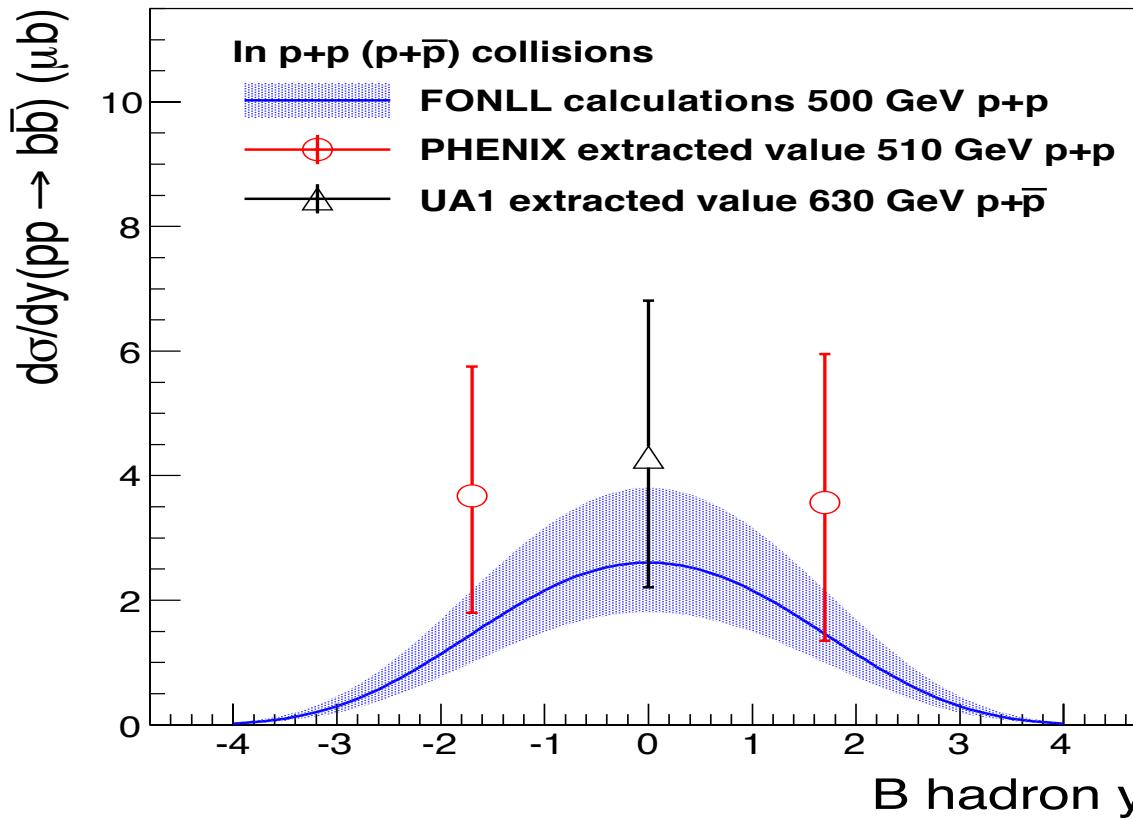


PHENIX arXiv:[1701.01342](https://arxiv.org/abs/1701.01342)



- The forward B->J/ $\psi$  fraction measured at PHENIX in 510 GeV p+p collisions is in reasonable agreements with the FONLL+CEM model calculation.
- The PHENIX result in 510 GeV p+p collisions is comparable with higher energy measurements.

# $b\bar{b}$ cross section in 510 GeV p+p data



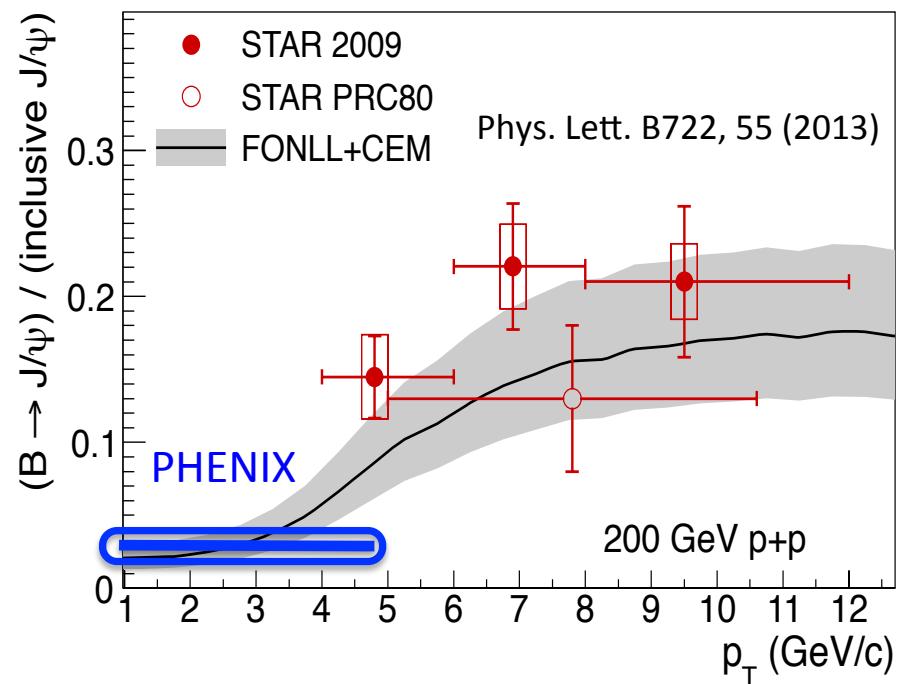
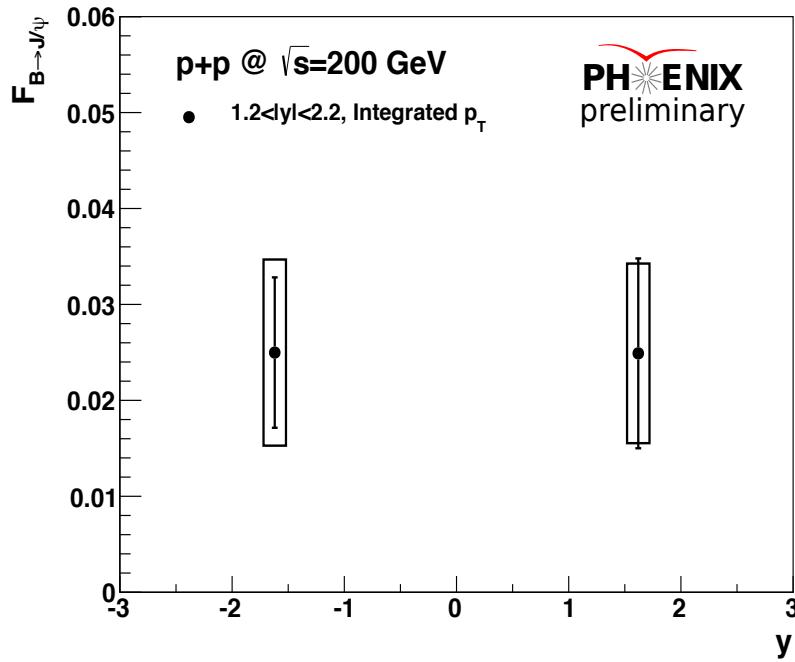
PHENIX arXiv:1701.01342

FONLL:  
M. Bedjidian et al. (2004),  
hep-ph/0311048

- The  $bb$  cross section is determined by the measured  $B \rightarrow J/\psi$  fraction ( $p_T > 0$  GeV/c) at PHENIX and extrapolated inclusive  $J/\psi$  cross section in 510 GeV p+p collisions.
- Good agreements with the FONLL model calculations, and comparable with UA1 results.

# B->J/ $\psi$ fraction in 200 GeV p+p data

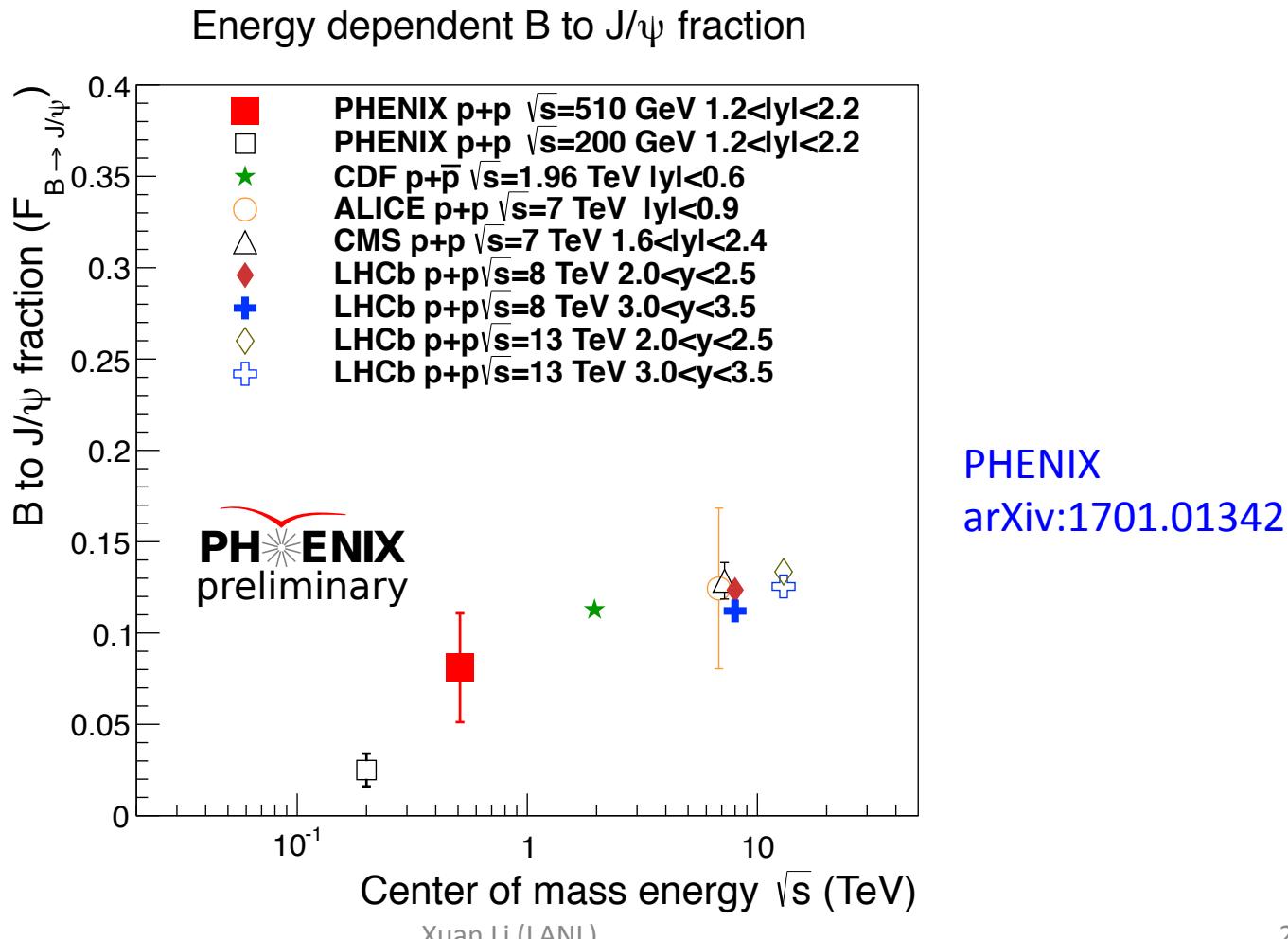
- Using the same method, PHENIX just achieves the preliminary result of the B->J/ $\psi$  fraction in 200 GeV p+p collisions within the kinematic regions of J/ $\psi$   $p_T < 5\text{GeV}/c$  and  $1.2 < |y| < 2.2$  rapidity.



- Both **STAR** and **PHENIX** measured B->J/ $\psi$  fractions are in reasonable agreements with the FONLL+CEM calculation.

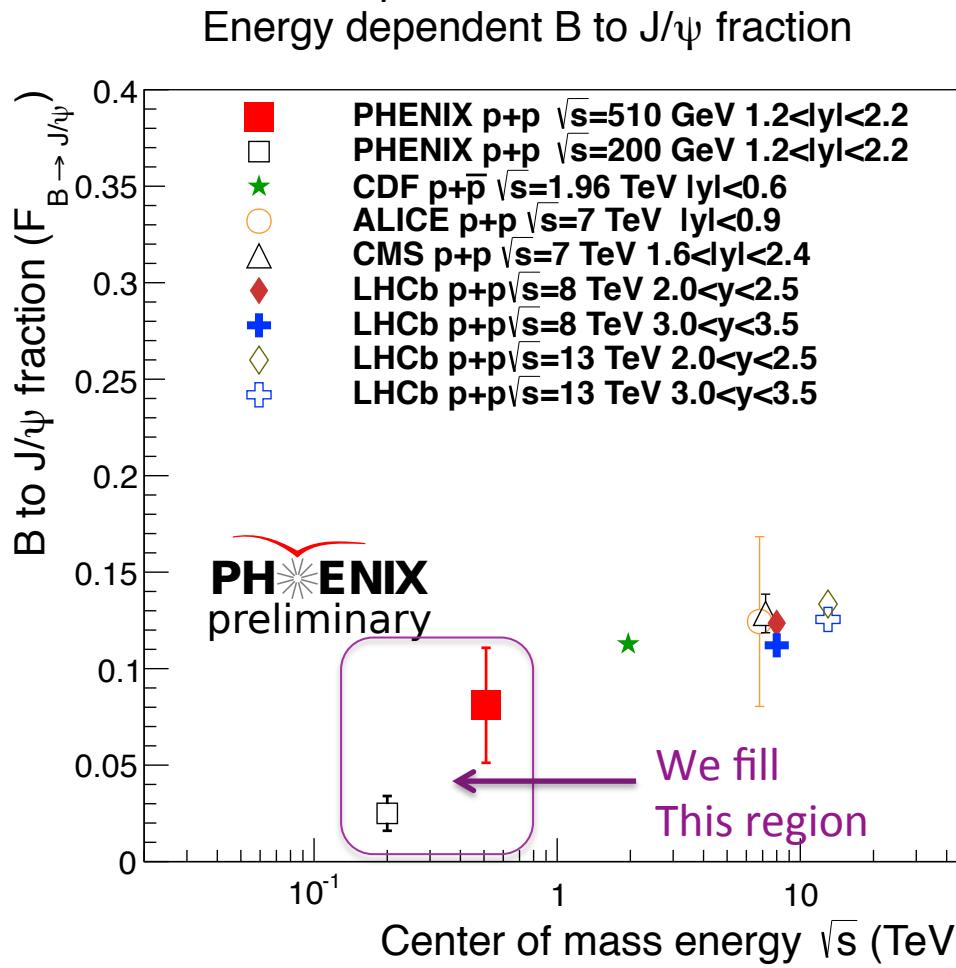
# Center of mass energy dependent $B \rightarrow J/\psi$ fraction

- A smooth energy dependence is found from 0.2 to 13 TeV p+p (p+pbar) collisions for  $B \rightarrow J/\psi$  fraction measured with  $J/\psi p_T < 5 \text{ GeV}/c$ .



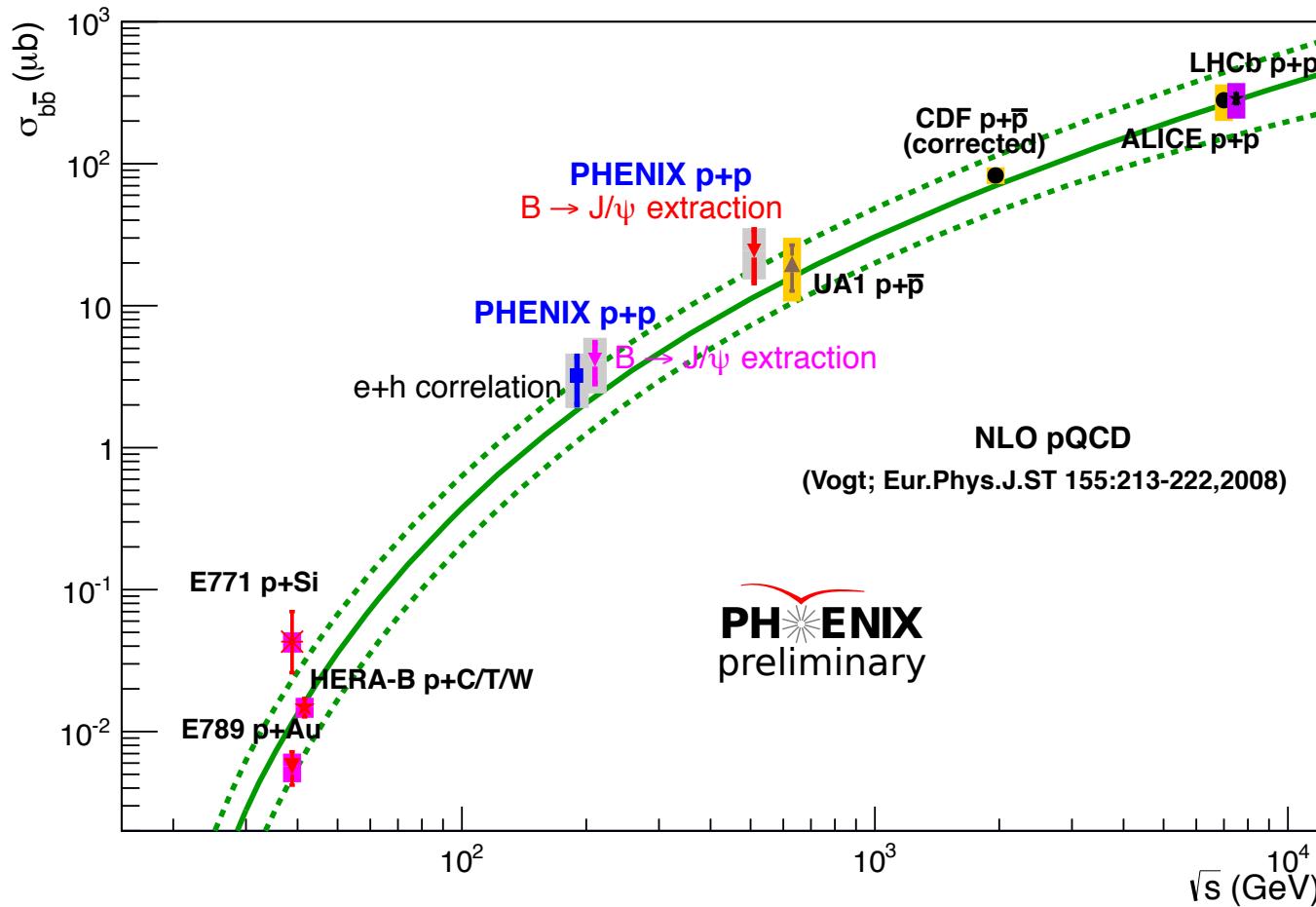
# Center of mass energy dependent $B \rightarrow J/\psi$ fraction

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# Center of mass energy dependent $b\bar{b}$ cross section

- The extracted  $b\bar{b}$  cross section results based on the  $B \rightarrow J/\psi$  fractions measured in 200 and 510 GeV p+p collisions are in reasonable agreements with the NLO pQCD predictions.

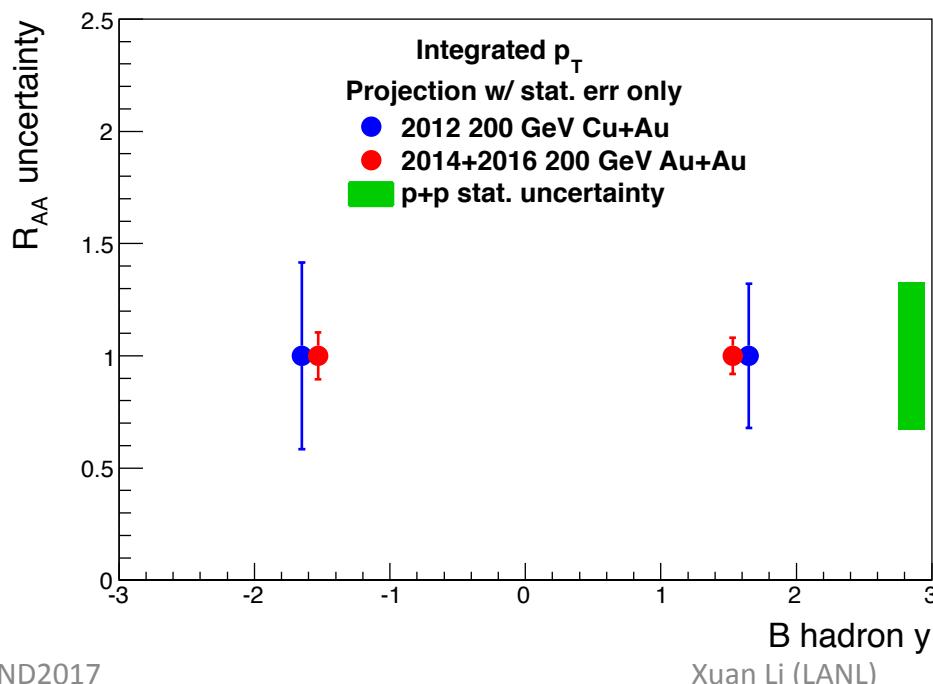


# B->J/ $\psi$ fraction in Cu+Au and Au+Au collisions

- The 2012 200 GeV Cu+Au analysis is being finalized. The 2014/2016 200 GeV Au+Au data production is ongoing.
- The nuclear modification factor  $R_{AA}$  can be derived from the B->J/ $\psi$  fraction and the inclusive J/ $\psi$   $R_{AA}$  according to this formula:

$$R_{CuAu/AuAu}^{B \rightarrow J/\psi} = \frac{F_{B \rightarrow J/\psi}^{CuAu/AuAu}}{F_{B \rightarrow J/\psi}^{pp}} R_{CuAu/AuAu}^{inc.J/\psi}$$

$R_{AA}$  projection of uncertainties

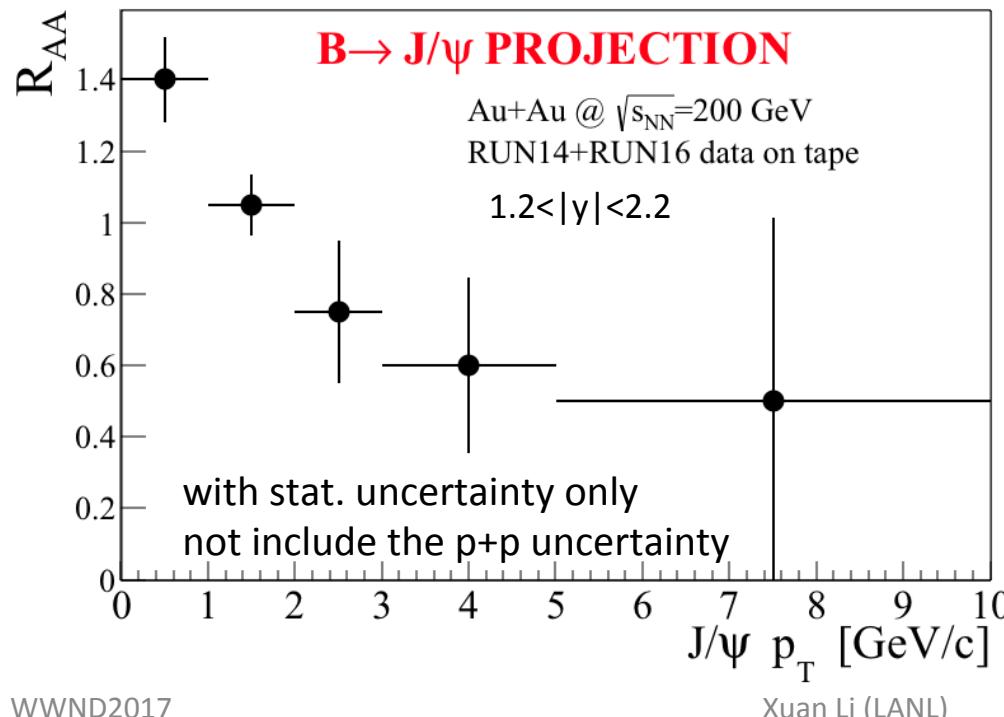


- The B hadron  $R_{AA}$  through the B->J/ $\psi$  measurements will improve the knowledge of bottom quark energy loss in QGP.

# B->J/ $\psi$ fraction in Cu+Au and Au+Au collisions

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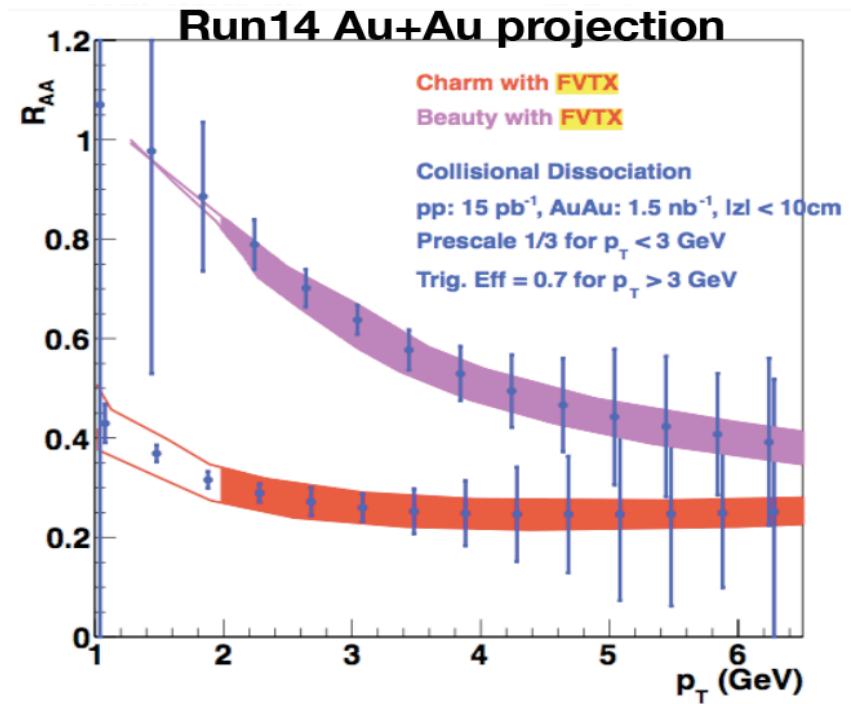
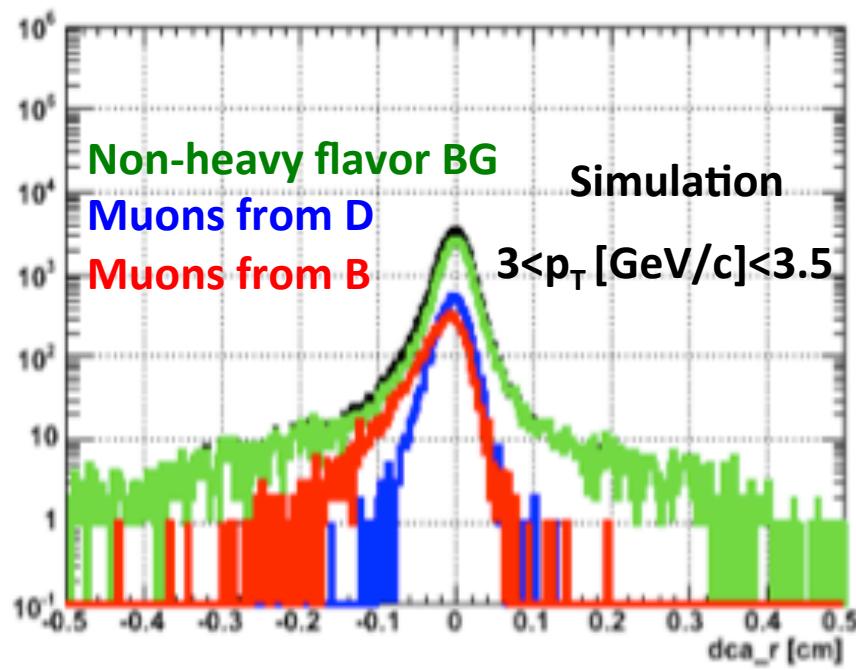
$$R_{CuAu/AuAu}^{B \rightarrow J/\psi} = \frac{F_{B \rightarrow J/\psi}^{CuAu/AuAu}}{F_{B \rightarrow J/\psi}^{pp}} R_{CuAu/AuAu}^{inc. J/\psi}$$



- The B hadron  $R_{AA}$  through the B->J/ $\psi$  measurements will improve the knowledge of bottom quark energy loss in QGP.

# Charm and Bottom decayed inclusive single muons

- High statistics measurement with similar method developed in the B to J/ $\psi$  analysis.
- Extend to high  $p_T$  region to determine the  $p_T$  dependence for **charm** and **bottom** production.
- Analysis is underway.
- The challenge is to minimize systematics.



# Summary

- First measurement of  $J/\psi$  from  $B$  decays in forward/backward rapidity with integrated  $p_T$  are achieved in both 510 GeV ([arXiv:1701.01342](https://arxiv.org/abs/1701.01342)) and 200 GeV  $p+p$  collisions.
  - A smooth center of mass energy dependence is found for integrated  $p_T J/\psi$  from  $B$ -meson decay in  $p+p$  ( $p + p\bar{p}$ ) collisions from 0.2 to 13 TeV.
  - Indication of a smooth transition from LO process to NLO process for bottom production is found through the  $B$  to  $J/\psi$  measurements.

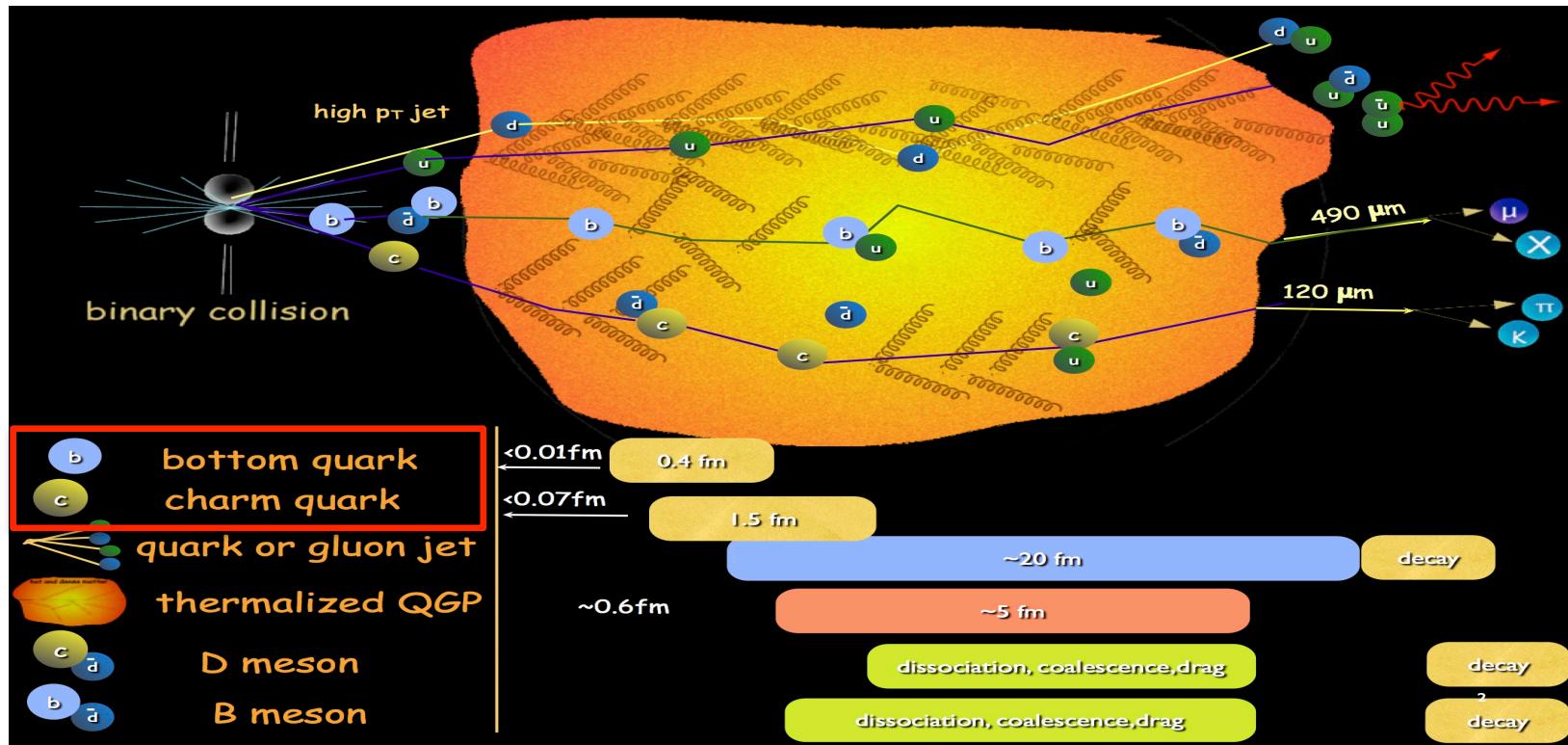
# Outlook

- The 200 GeV Cu+Au B to J/ $\psi$  paper preparation is ongoing, the final result is expected to be released soon.
- Large data sets in various types of collision systems collected at PHENIX provide opportunities to study
  - Forward/backward B to J/ $\psi$  via di-muon channel in 2015 p+Au, 2014/2016 Au+Au collisions to understand CNM and QGP effect.
  - Study the D/B separated single muons in 2012/2015 p+p, 2015 p+Au and 2014/2016 Au+Au collisions with higher statistics will help understand the charm and bottom production and the mass dependent energy loss in QGP.

# Backup

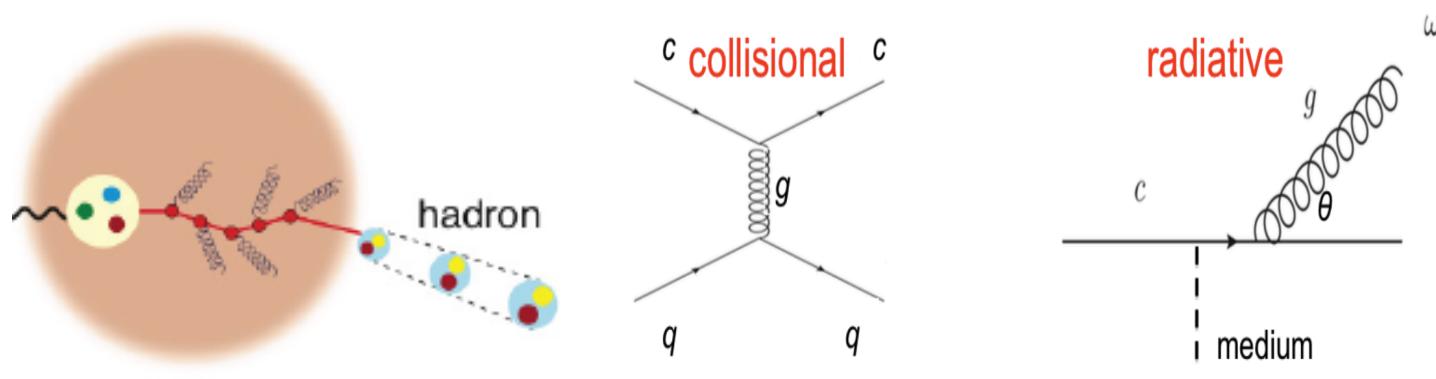
# Advantages to use **heavy quarks** to scan the QGP

- Short wavelength which can probe the small scale volume ( $<5\text{fm}$ ). Uncertainty principle:  $m_c \approx 1.3 \text{ GeV}$  and  $m_b \approx 4.6 \text{ GeV}$ .
- Formed before the QGP creation ( $<1\text{fm}/c$  after the Big-Bang) to study the full evolution.
- Probes that can cross the plasma and don't vanish.



# Energy loss in the QGP

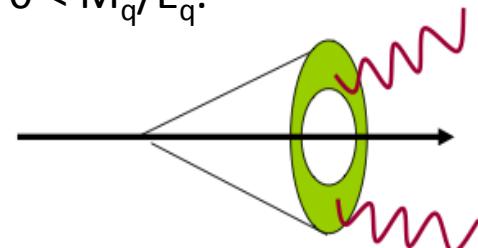
- Energy loss Mechanism:
- (I) Heavy quarks lose energy when crossing the medium (indicated by the  $R_{AA}$  suppression).



- Due to the dead cone effect, the energy loss in the medium is mass dependent:

$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

Dead cone effect: gluon radiation from massive quarks suppressed at angle  $\theta < M_q/E_q$ .

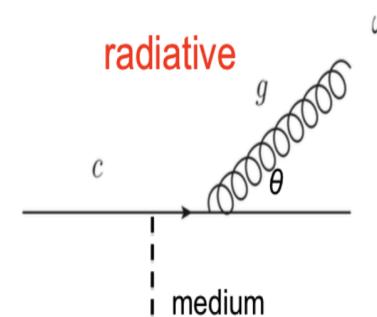
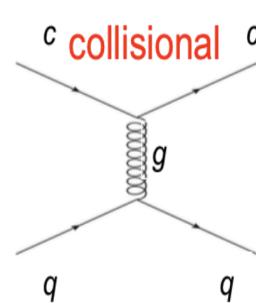
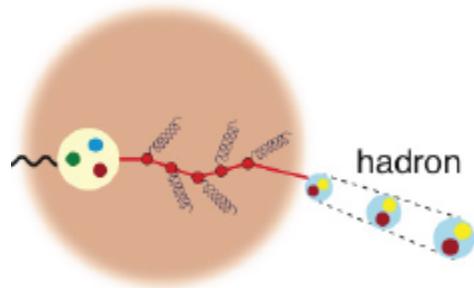


# Energy loss in the QGP

- Energy loss Mechanism:
- (II) Shorter formation and dissociation time of b(c) quark to B(D) from light quark hadrons.

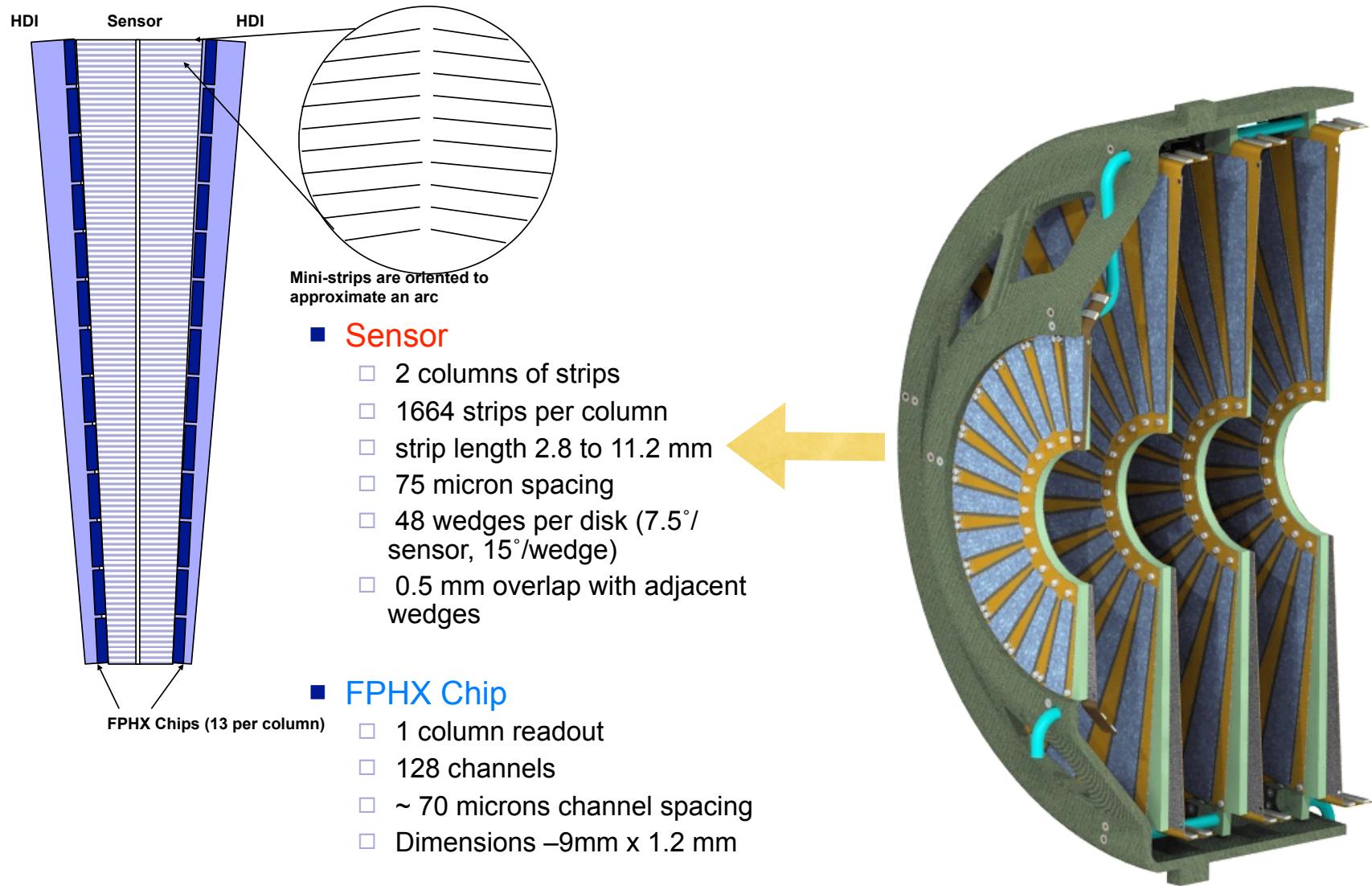
$$\Delta E_g > \Delta E_{u.d.s} > \Delta E_c > \Delta E_b$$

A.Adil, I.Vitev, Phys. Lett. B649 (2007)



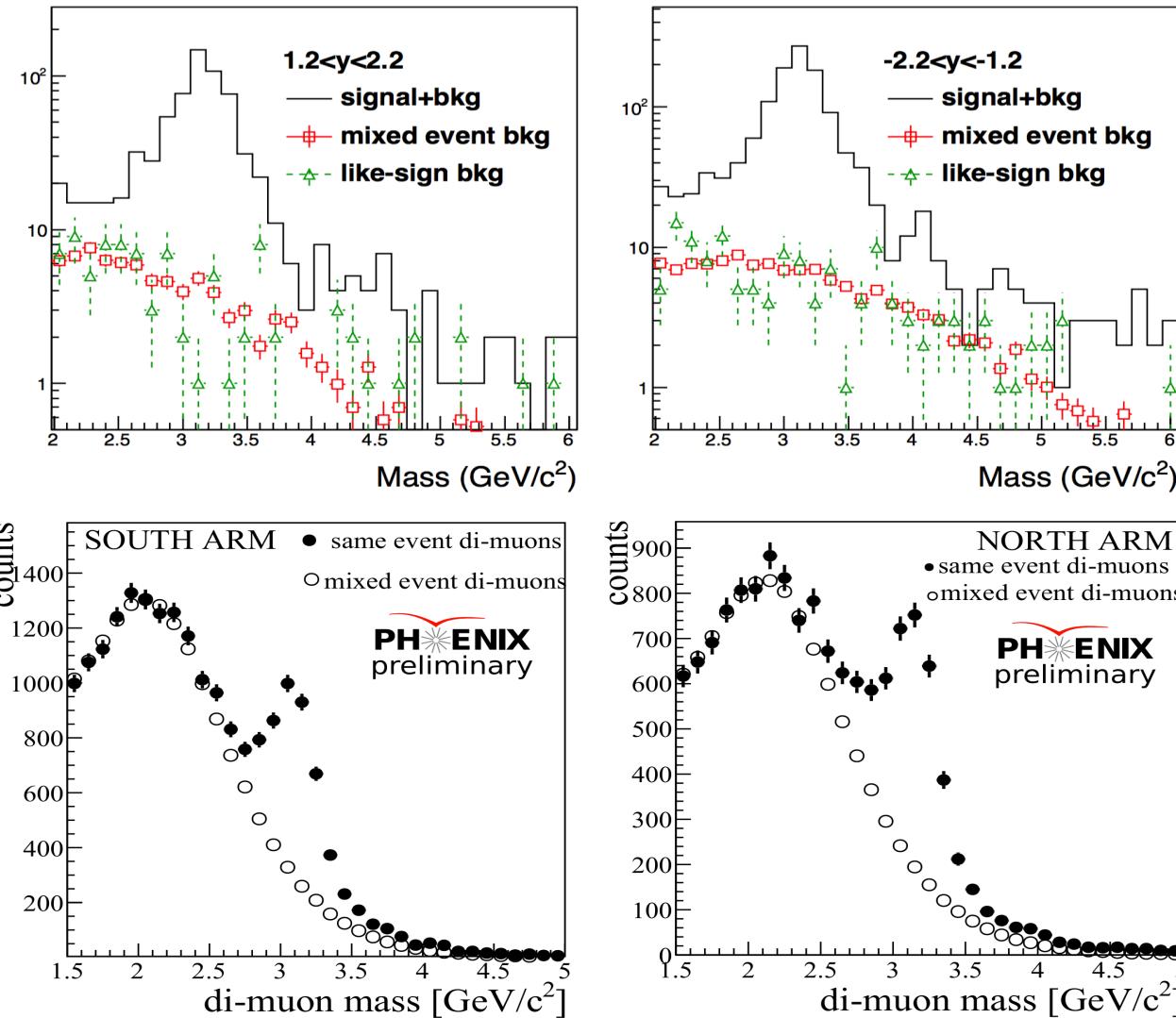
- Mass effect is negligible at high  $p_T$  but not in low  $p_T$  region.
- Low  $p_T$  heavy flavor production is dominated by charm, need to separate charm and bottom and study the mass/flavor dependence.

# The Forward Vertex Detector (FVTX)



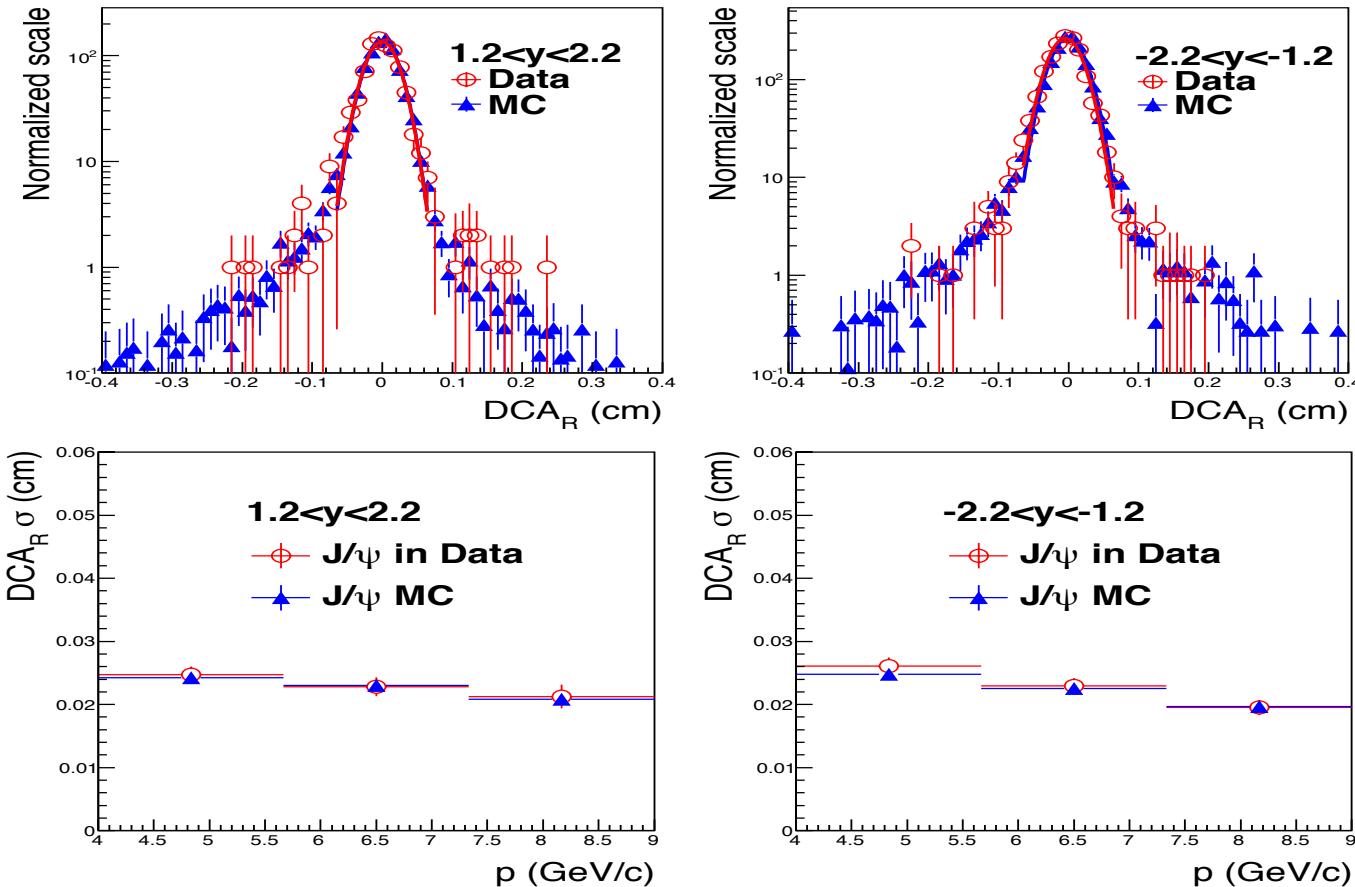
# Invariant mass of di-muons

- In 2012 510 GeV p+p (top) and Cu+Au (bottom) data.



# Comparison of DCA(r) between data and simulation (p+p)

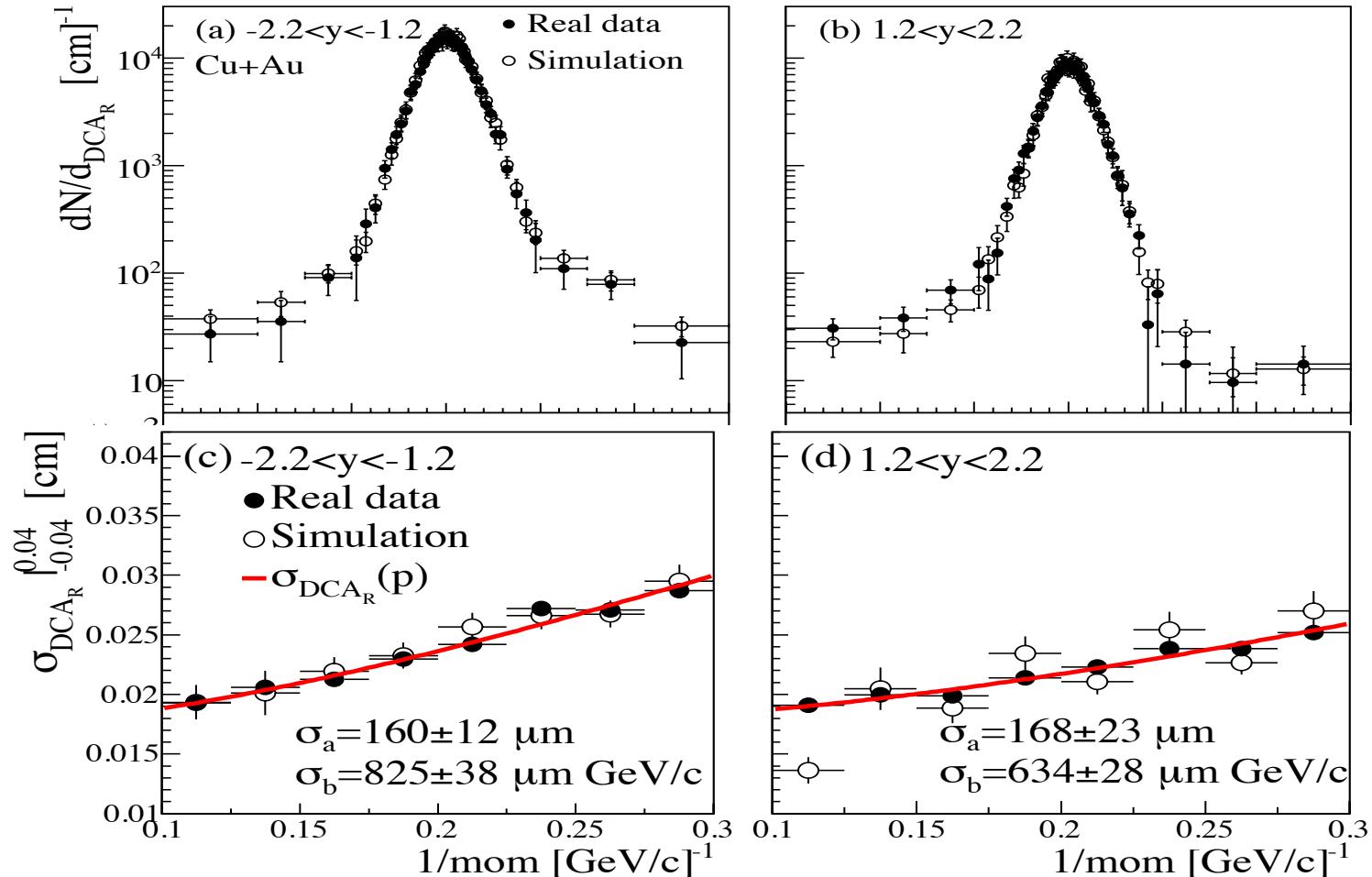
- DCA(r) of J/ $\psi$  decayed muons with integrated p and p dependence.
- Fit the DCA(r) core region to extract the DCA(r) resolution.



- Good agreement between data and simulation for DCA(r) resolution.

# Comparison of DCA(r) between data and simulation (Cu+Au)

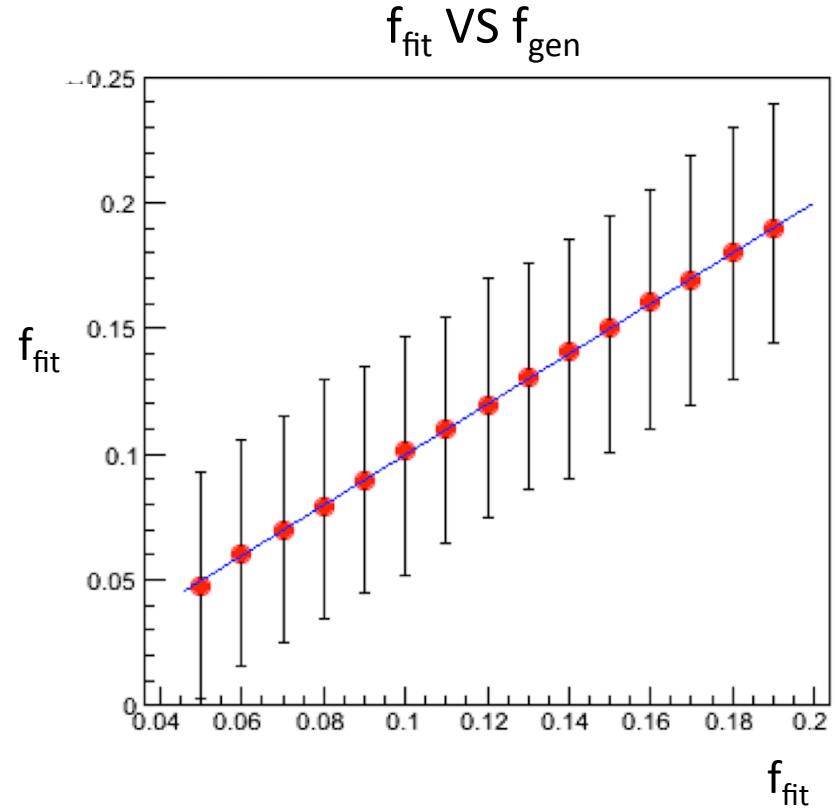
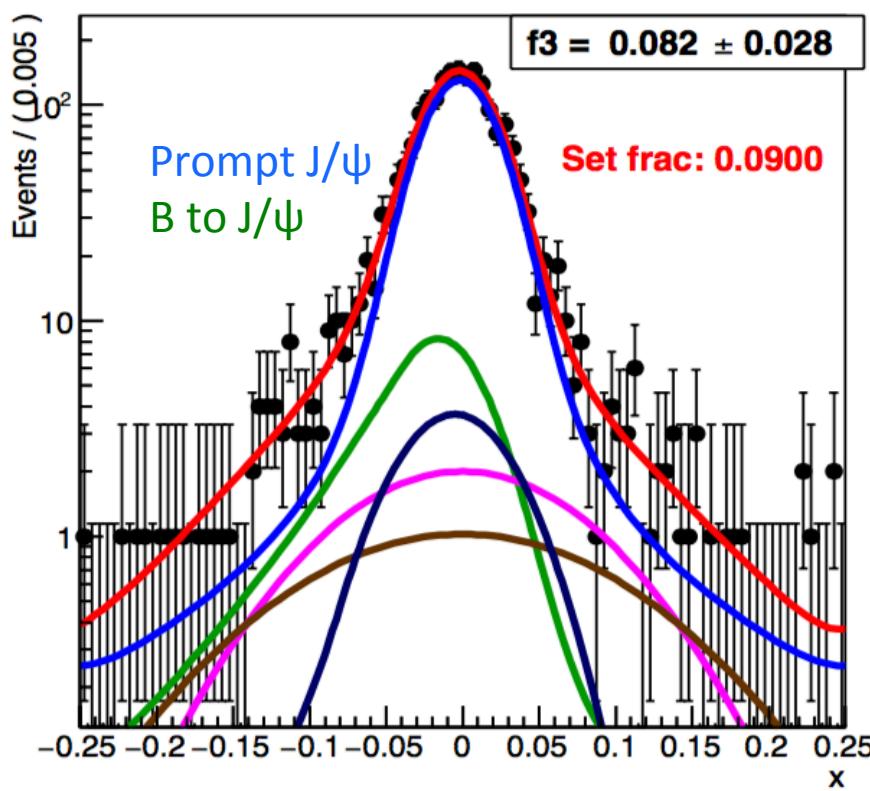
- DCA(r) of stopped hadrons with integrated p and p dependence.
- Fit the DCA(r) core region to extract the DCA(r) resolution.



- Good agreement between data and simulation for DCA(r) resolution.

# Test the fit package in Toy MC

- Generate pseudo-data according to the shape of foreground and background. Use the same fit packages applied in data.

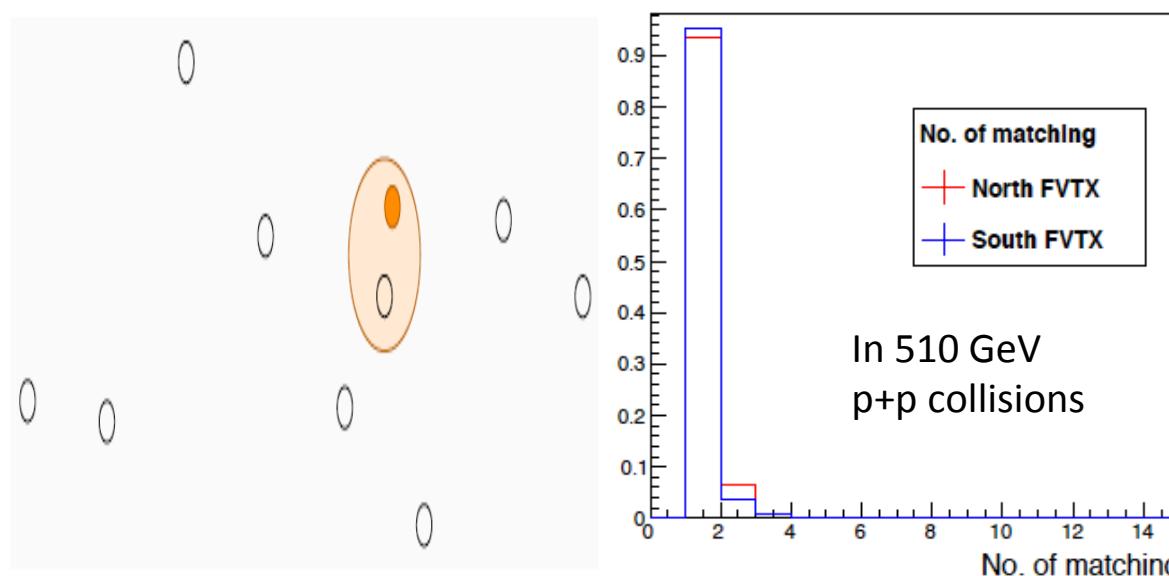


- Good linearity between generated and B to J/ $\psi$  ratio.
- Final results from data are under collaboration review.

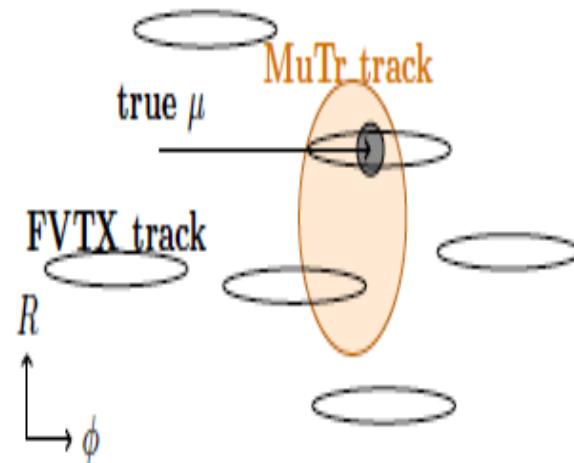
# FVTX-MuTr mis-matching background determination

- For one MuTr track, there is a probability of finding more than one FVTX track within the matching window.

In 510 GeV p+p collisions



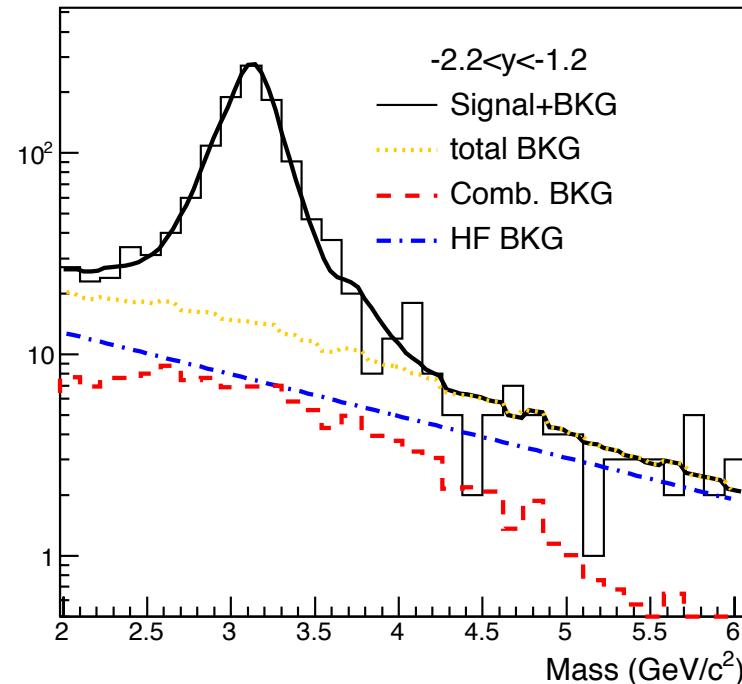
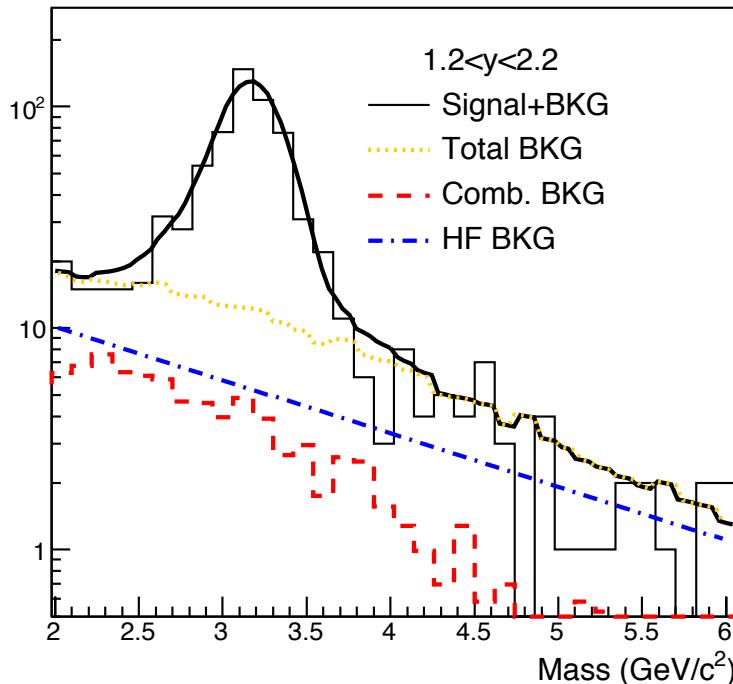
In 200 GeV Cu+Au collisions



- In p+p collisions, the probability to have more than one FVTX track matched with the MuTr track is around or less than 5%.
- In heavy ion collisions such as Cu+Au collisions, the probability is much higher.

# HF continuum background determination (510 GeV p+p)

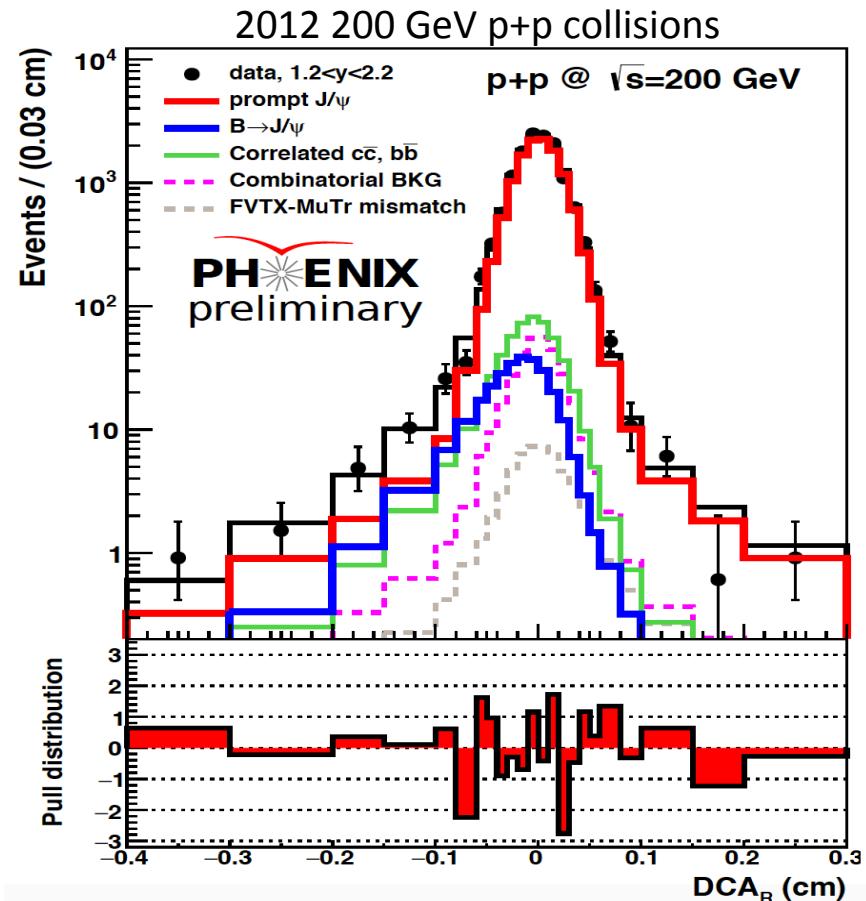
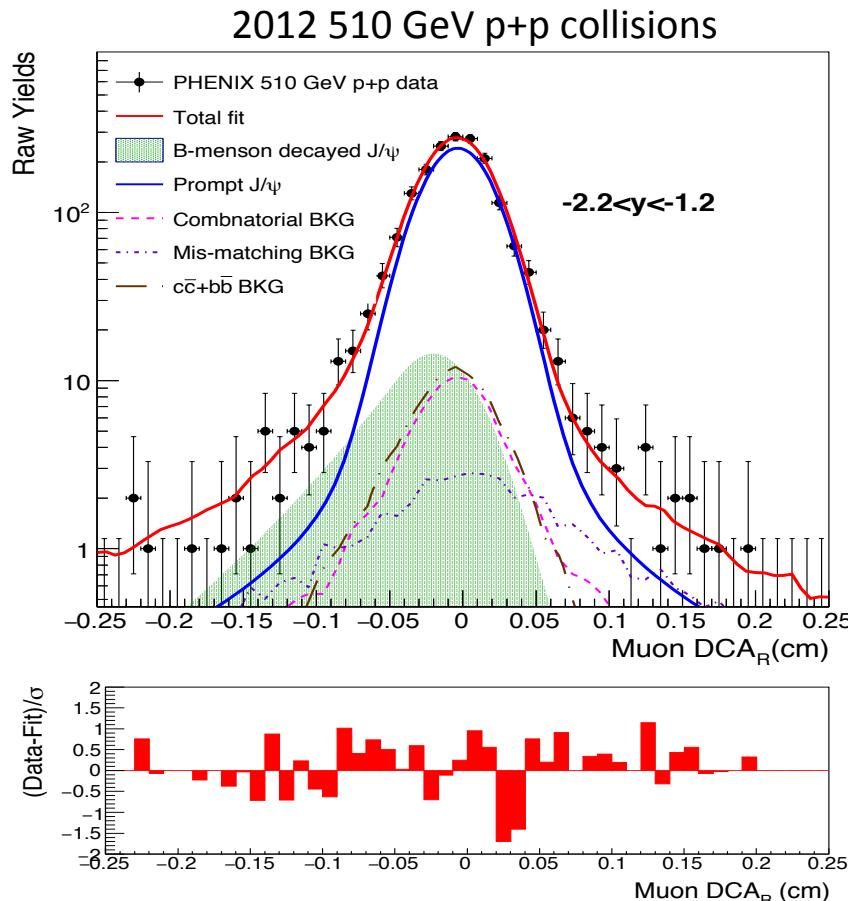
- Fit the di-muon mass to extract the HF continuum background.



- Total background consists of HF continuum background and mixed event background.
- HF continuum background is comparable with the mixed event background within the mass cut window.

# Analysis strategy for the B to J/ $\psi$ ratio measurement (III)

- Fit on  $DCA_R$  in data to simultaneously determine the **prompt J/ $\psi$**  and **J/ $\psi$  from B-meson decay** yields and extract the B to J/ $\psi$  fraction.

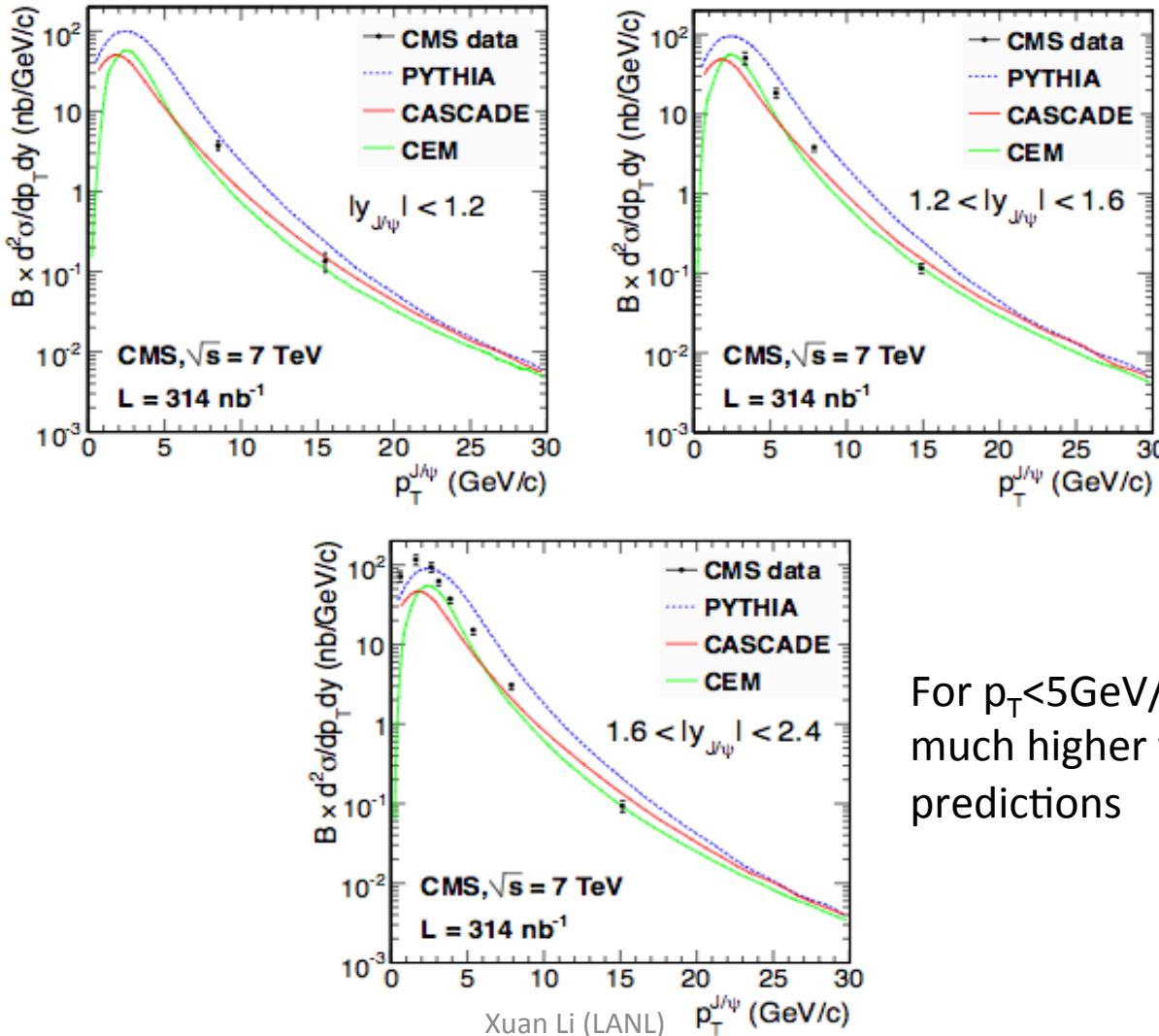


# Extracted total $b\bar{b}$ cross section as a function of center of mass energy

- Use the PPG104  $d\sigma/dy$  to evaluated inclusive J/ $\psi$  cross section within  $1.2 < |y| < 2.2$  at 200 GeV.
- Scale from 200 GeV to 500 GeV according to CEM total inclusive J/ $\psi$  cross section calculation.
- Divide this value by the PDG  $b \rightarrow J/\psi$  branching ratio  $1.09 \pm 0.32\%$ .
- Scale the cross section within  $1.2 < |y| < 2.2$  to the full rapidity range and scaling factor is calculated based FONLL calculations.

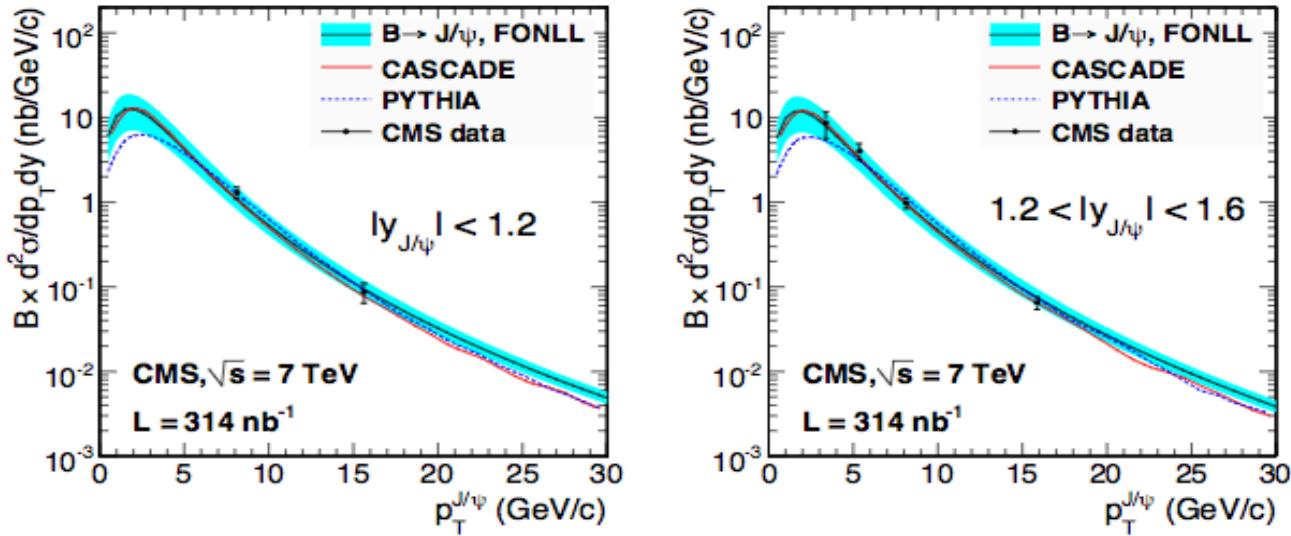
# But, something beyond current theory

- CMS 7 TeV prompt J/ $\psi$  cross section.

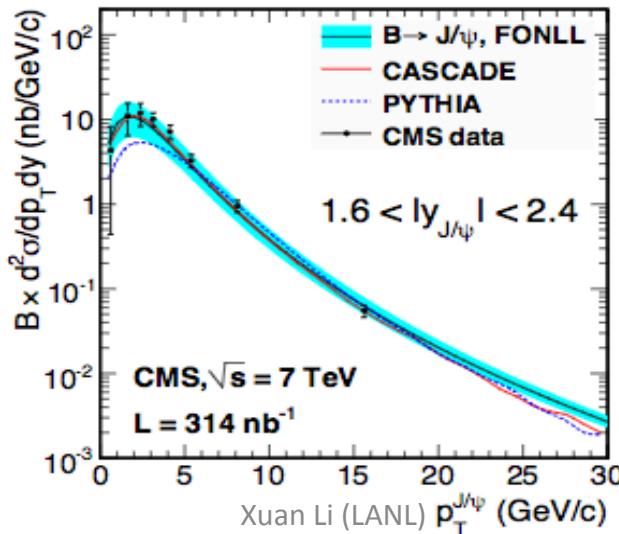


# But, something beyond current theory

- CMS 7 TeV Non prompt J/ $\psi$  (from B decay) cross section



Expect to see lower  
B to J/ $\psi$  fraction at  
LHC than theory  
predictions.



For  $p_T < 5 \text{ GeV}/c$ , data are  
on the top edge of theory  
predictions